**Earth Science Division**

***Strategic Goal 2:  Advance understanding of Earth and develop technologies to improve the quality of life on our home planet.***

***Objective 2.2: Advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet.***

**TABLE OF CONTENTS**

Carbon Cycle & Ecosystems Page 3

Atmospheric Composition Page 11

Climate Variability and Change Page 14

Earth Surface & Interior Page 21

Weather Page 28

Water & Energy Cycle Page 34

**FY 2015 ES-15-1:** Demonstrate planned progress in advancing the understanding of changes in Earth’s radiation balance, air quality, and the ozone layer that result from changes in atmospheric composition.

**FY 2015 ES-15-3:** Demonstrate planned progress in improving the capability to predict weather and extreme weather events.

**FY 2015 ES-15-6:** Demonstrate planned progress in detecting and predicting changes in Earth’s ecological and chemical cycles, including land cover, biodiversity, and the global carbon cycle.

**FY 2015 ES-15-7:** Demonstrate planned progress in enabling better assessment and management of water quality and quantity to accurately predict how the global water cycle evolves in response to climate change.

**FY 2015 ES-15-9:** Demonstrate planned progress in improving the ability to predict climate changes by better understanding the roles and interactions of the ocean, atmosphere, land, and ice in the climate system.

**FY 2015 ES-15-11:** Demonstrate planned progress in characterizing the dynamics of Earth’s surface and interior, improving the capability to assess and respond to natural hazards and extreme events.

**Annual Performance Indicator ES-15-6: Demonstrate planned progress in detecting and predicting changes in Earth’s ecological and chemical cycles, including land cover, biodiversity, and the global carbon cycle.**

NASA research in the Carbon Cycle and Ecosystems focus area continues to increase knowledge of changes in Earth’s biogeochemical cycles, ecosystems, land cover, and biodiversity. Satellite observations are used to detect and quantify these changes and, when used within numerical models, to improve our ability to predict impacts, future changes and feedbacks, and consequences for society. Highlights of research conducted in the past year are summarized below.

The Arctic region’s chemistry, biology, and ecology are subject to and responding to climate variability and change. Many papers are beginning to detail shifts in the Arctic Ocean system that are characterized by the persistent decline in the ice thickness and summer extent of sea-ice cover, and a warmer, fresher, and more acidic upper ocean as well as terrestrial ecosystem and atmospheric shifts. There is growing evidence that those changes are forcing marine ecosystems in the Arctic toward new and generally unknown states chemically and ecologically. In 2015, NASA continued its investment in the science of the Carbon in Arctic Reservoirs Experiment (CARVE). The CARVE airborne campaign is elucidating the seasonal dynamics and environmental controls of methane and carbon dioxide (carbon cycle) emissions in Alaskan Arctic and boreal ecosystems.  Chang et al., (2014) found that Alaska emitted less than 2% of the total global methane flux during the 2012 growing season, despite widespread permafrost thaw and other evidence of climate change in the region. McEwing et al., (2015) attributed methane emissions across Arctic ecosystems and Henderson et al., (2015) described a high-resolution atmospheric transport model for quantifying carbon cycle dynamics in the high latitudes. Additionally, Veraverbeke et al., (2015) reported the development of the Alaska Fire Emissions Database (AKFED), a daily burned area and fire carbon emissions database for Alaska, provided new opportunities to quantify environmental controls on daily fire dynamics and their feedbacks to changing disturbance patterns as well as biogeochemical model development.  Rogers et al., (2015) reported that different tree species in the North American versus Eurasian boreal forests have significant influences on fire regimes in those domains, respectively. The CARVE project has achieved 500 hours of science flights on thedetailed measurements of important greenhouse gases on local to regional scales in the Alaskan Arctic. CARVE will continue to demonstrate new remote sensing and improved modeling capabilities to quantify Arctic carbon fluxes and carbon cycle-climate processes.

Synthesis findings from the 2011-2012 Impacts of Climate on the EcoSystems and Chemistry of the Arctic Pacific Environment (ICESCAPE) field campaign are fully documented in a 2015 special issue of Deep-Sea Research II (Arrigo (Ed), August 2015). The special issue is entitled, “Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment (ICESCAPE)”. The study area included the Beaufort and Chukchi Seas as well as a portion of the Bering Strait. Over the last five years, the science team involved in the program addressed key scientific issues in the ICESCAPE study regions, including changes in sea ice cover, changes in primary production, nutrient dynamics, carbon cycling, and improvements to remote sensing and modeling. ICESCAPE data have confirmed that sea ice morphology has undergone a regime shift over a decadal time scale, transitioning from a multi-year to thinner, first year-dominated seasonal sea ice pack in the Chukchi Sea (Polashenski et al, 2015). As a result of this thinning of the sea ice there are recent increases in open water, leading to higher rates of annual primary production, which reached a peak in 2011 (Arrigo and Van Dijken, in press). Productivity in this area is portioned in to the surface and subsurface layer in summer, during which nutrients become depleted; Brown et al, (2015) undertook the first comprehensive analysis of the subsurface chlorophyll maximum (SCM) in the Chukchi Sea, revealing a shallower SCM (peak productive area) than the surrounding Canada Basin. NASA also supported the development and implementation of biogeochemical models that can be used to understand and predict changes in the major elemental cycles (carbon) that are likely to be manifested in the face of continued anthropogenic perturbations. Zhang et al. (2015) showed that shelf-break upwelling helped to sustain the large under-ice phytoplankton blooms (reported in 2014) that were observed as part of the field program. The papers in the special issue (e.g., Arrigo et al., 2015; Brown et al. (2015a), Brown et al. (2015b), Chaves et al. (2015), Gong and Pickart (2015), Lowry et al. (2015), Polashenski et al. (2015), Matsuoka et al. (2015), Mills et al. (2015), Zhang et al. (2015)) explore biological, physical, and chemical dynamics of the western Arctic Ocean (Beaufort and Chukchi Seas), examining drivers of primary production and factors affecting ocean optics, ocean acidification, ocean physics, and sea ice/ice edge dynamics. A second synthesis volume is due later in 2015, and will discuss additional details regarding the possible natural and anthropogenic drivers of the change to sea ice, ice sheets, and the surrounding oceans’ biology and biogeochemistry.

Remote sensing research on processes controlling variations in the terrestrial carbon cycle continues within the NASA Terrestrial Ecology program. Significant research findings that integrated ground observations with modeling results provided new insights on the processes and environmental drivers of anthropogenic and natural carbon cycle dynamics of the terrestrial biosphere. Ground and aircraft measurements showed that the seasonal magnitude of carbon dioxide (CO2) concentrations increased by as much as 50% over the past 50 years. Gray et al. (2014) showed that up to one-quarter of these observed changes are due to a 240 percent increase in Northern Hemisphere extra-tropical crop production (maize, wheat, rice, and soybean) between 1961 and 2008, which increased the amount of cropland net uptake of carbon during the Northern Hemisphere growing season by 0.33 petagrams. Kort et al. (2014) used satellite observations to identify a persistent atmospheric methane anomaly in the Four Corners region of the Southwestern U.S., which was attributed to increases in natural gas production. Evaluation and verification of natural (biogenic) greenhouse gas inventories was reported by Ogle et al., (2015) for the mid-continental region of the U.S. This research found that the estimated flux generated from a biogenic emissions inventory (an uptake of 408 ± 136 Tg CO2 for the entire study region) was not statistically different from the biogenic flux estimated using the atmospheric CO2 concentration data (an uptake of 478 ± 146 Tg CO2). Schimel et al. (2015) analyzed the effects of atmospheric CO2 on the terrestrial carbon cycling to determine where carbon observations are lacking (e.g., the tropics) are likely where the greatest uncertainties lay.

Remote sensing research continues on the ecological and societal impacts of wildfire and other natural disturbances. Using satellite-remote sensing products, Paveglio et al. (2015) found that vegetation cover was more important than weather in controlling the severity of fires in forests in central Idaho and western Montana forests. Turner et al. (2015) showed that between 1991 and 2010, 13% of the forests in western Oregon were disturbed by harvest, fire, pest and pathogens. While over the entire study period, these forests were a net sink of atmospheric carbon; during large fire years they were a net atmospheric source of atmospheric carbon. Rogers et al. (2015) reported that because of differences in forest type and plant community structure, boreal forests in North America were more vulnerable to high intensity crown fires than those in Eurasia. Recent studies have indicated an increasing vulnerability of tundra to wildfire due to increasing temperatures and longer growing seasons, and consequences of changes in past and future fire regimes was reviewed by French et al., (2015) for resource management in Alaskan tundra ecosystems. Birch et al. (2015) developed wildfire impact assessment strategies needed for developing baselines for adaptation and societal response to wildfire impacts in the western U.S.

Several important 2015 publications examined linkages of land cover/land use change practices, the urban environment and climate change. Urban areas are becoming more densely populated, and thus the impacts and feedbacks of population increases and land cover/land use change practices in cities require further study. In the first example, city structure was found to influence seasonal green-up differently by region (Walker et al., 2015)**.** Investigators from South Dakota State University and University of Oklahoma analyzed the relationship between the progress of accumulated springtime temperatures and satellite observations of landscape greenness in and around 51 cities across the US Great Plains during 2002-2012. Results revealed that urban intensity, as measured by the proportion of impervious surface area, influences the seasonal progression of landscape greenness differently depending regional climate. In the southern Great Plains (Oklahoma and Texas), a higher proportion of impervious surface area was linked with later peak greenness; whereas, in the central Great Plains (Missouri, Iowa, Nebraska), a higher proportion of impervious surface area in the city was linked to earlier peak greenness. Farther north (North Dakota and Minnesota), no significant relationship was observed. These geographic patterns of the onset of greenness emerged from a complex interaction of temperature gradients and moisture availability. A second paper examined the satellite-based view of urban expansion in East–Southeast Asia, currently one of the fastest urbanizing regions in the world. The regional population expansion suggests built-up land expansion, however, spatially-and temporally-detailed information on regional-scale changes in urban land or population distribution do not exist. A new data set was created that features urban land extent for 2000 and 2010, downloadable by country, or as a mosaic (250m), with maps at 500m and 1km resolution from MODIS observations.  A global map of urban expansion by continent will be released in late 2015.  Schneider et al. (2015) concluded that although urban land expanded at unprecedented rates, urban populations grew more rapidly, resulting in increasing densities for the majority of urban agglomerations, including those in both more developed (Japan, South Korea) and industrializing nations (China, Vietnam, Indonesia). This result contrasts previous sample-based studies, which conclude that cities are universally declining in density. The patterns and rates of change uncovered by these datasets provide a unique record of the massive urban transition currently underway in East–Southeast Asia that is impacting local-regional climate, pollution levels, water quality/availability, arable land, as well as the livelihoods and vulnerability of populations in the region. Other methodologies have also been developed to determine and detect change in urban areas at continental scales using the high resolution bands of MODIS imagery (Mertes et al., 2015). Also in the area of urban growth, the PO Plain EXperiment (POPLEX) is a research project on mega urban changes and impacts of these changes on the local environment.  Innovative data processing and use of QuikSCAT satellite data in a paper by Stevenazzi et al. (2015) allowed successful development of a spatially and temporally consistent dataset delineating urban extension. The data set allows researchers to monitor the annual degree of urban changes in a 1-km grid for the decade of 2000-2010. These high-quality satellite data products enable quantitative evaluations of environmental changes over large urban areas in a time and space continuum without gaps.

Terrestrial and aquatic ecosystems respond to climate variability and change, including impacts on species distribution and biodiversity. Arctic marine mammal population status and sea ice habitat loss were examined in a paper by Laidre et al. (2015). Arctic marine mammals (AMMs) are icons of climate change, largely because of their close association with changing sea ice and utilization by native people. The team found that among AMM subpopulations, 78% are legally harvested for subsistence purposes, and changes in sea ice phenology have been profound. In all regions except the Bering Sea, the duration of the summer (i.e., reduced ice) period increased by 5–10 weeks and by >20 weeks in the Barents Sea between 1979 and 2013. In light of generally poor data, the importance of human use, and forecasted environmental changes in the 21st century, the researchers recommend conservation approaches. Another paper addressed the impacts of socioeconomic changes on habitats and ecosystems. A University of Wisconsin team analyzed population trends of eight large mammals in Russia from 1981 to 2010 (i.e., before and after the collapse of the Soviet Union - Bragina et al., 2015). The paper found a rapid increase of the grey wolf population likely attributable to the cessation of governmental population control.  Findings also conclude that widespread decline in other wildlife populations after the collapse of the Soviet Union demonstrate the magnitude of the effects that socioeconomic shocks can have on wildlife populations and the possible need for special conservation efforts during such times. The impact of climate change on Earth’s ecosystems are also marked in the ocean. Climate change was found to influence global ocean plankton because it directly impacts both the availability of growth-limiting resources and the ecological processes governing biomass distributions and annual cycles (Behrenfeld, 2014). Forecasting this change demands recognition of different attributes of the plankton world. Findings stated that changes in phytoplankton division rates are paralleled by proportional changes in grazing, viral attack and other loss rates across the ecosystem. The paper defines a trophic dance between predators and prey in the ocean, how these dynamics dictate when phytoplankton biomass remains constant or achieves massive blooms, and how shifting predator/prey dynamics can determine the sign of change in ocean ecosystems under a warming climate. Understanding these dynamics of the plankton under a variable and changing climate will have direct impact on high-level ecosystems, including fisheries. Finally, to further examine the vulnerability and resilience of terrestrial ecosystems, a large-scale study of ecosystem responses to environmental change in western North America’s Arctic and boreal region is beginning. This study will have implications for social-ecological systems. The Arctic-Boreal Vulnerability Experiment (ABoVE, http://above.nasa.gov) is a major NASA field campaign to take place in Alaska and western Canada during the next five to eight years. ABoVE will seek a better understanding of the vulnerability and resilience of ecosystems and society to environmental changes in this region. The NASA Terrestrial Ecology program solicited a ROSES 2014 call for proposals to investigate ecosystem responses to environmental change in western North America’s Arctic and boreal region and the implications for social ecological systems. Selections for the field program are underway and the field program will begin in late 2015.

In the area of suborbital research, NASA is midway through its third year of high-altitude ER-2 aircraft flights in California to simulate data from the planned Hyperspectral Infrared Imager (HyspIRI) satellite mission ([http://hyspiri.jpl.nasa.gov](http://hyspiri.jpl.nasa.gov/)). The goals of the flights are to produce valuable precursor science in advance of the space mission and prepare the research community for HyspIRI by generating HyspIRI-like data sets from an airborne platform.  The combination of a visible to shortwave imaging spectrometer (Airborne Infrared / Visible Imaging Spectrometer, AVIRIS) and a thermal multispectral sensor (simulated by the MODIS/ASTER (MASTER) airborne simulator) offers the ability to distinguish among many components of ecosystems through optical expressions of chemical and physical traits, as well as providing insights into the rates of ecosystem processes mediated by temperature.  The California flights are collecting imagery that covers ecosystems ranging from high mountains to coasts and from very dry to very moist.  The flights are also looking at sea surface characteristics in the Santa Barbara Channel and Monterey Bay. Sampling has taken place during the severe droughts of the last year. While the use of suborbital NASA data has historically been focused on the terrestrial and atmospheric regions, NASA executed a field campaign in 2014 that utilized ships and aircraft to examine phytoplankton and carbon cycling in the ocean. The Ship-Aircraft Bio-Optical Research (SABOR) experiment examined the waters of the North Atlantic Ocean for three weeks during July and August 2014. The SABOR experiment brought together ocean and atmospheric scientists from government, university and industry. Measurements from within and above the North Atlantic Ocean allowed scientists to tackle the optical issues associated with characterizing phytoplankton, and distinguishing plankton from other material in the water, from space. The SABOR investigators have planned a special session at the upcoming Ocean Sciences Meeting (February 2016) and are also planning a coordinated set of synthesis publications (2016).

Coastal regions are dynamic and of great interest because of the changes they are experiencing due to human activities and climate change. The contribution of coastal margins to regional and global carbon budgets is not well understood, largely due to limited information about the magnitude, spatial distribution, and temporal variability of carbon sources and sinks in coastal waters. Accurate detection and quantification of coastal vegetation also poses complexities in satellite retrievals due to their mixed terrestrial and aquatic components. However, aquatic color radiometry remote sensing of coastal and inland water bodies is of great interest to a wide variety of research, management, and commercial entities as well as the general public. NASA has made investments to improve upon the retrievals of coastal water quality and optical properties. Recently, NASA has been interested in testing observational capability of its current Earth Observing satellite fleet in the area of water quality. Current satellite radiometers were primarily designed for observing the global ocean and not necessarily for observing coastal and inland waters. Therefore, deriving coastal and inland aquatic applications from existing sensors is challenging. Mouw et al. (2015) described the current and desired state of the science and identified unresolved issues in four fundamental elements of aquatic satellite remote sensing namely, mission capability, *in situ* observations, algorithm development, and operational capacity that need to be addressed to effectively remotely sense coastal and inland waters. Case studies have begun to examine the use of multiple satellite sensors in water quality and clarity retrievals using collocated matchups between Sea-viewing Wide Field-of-View Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS), and Suomi NPP Visible Infrared Imager Radiometer Suite (VIIRS) in the Gulf of Mexico (Barnes and Hu, 2015). The findings highlight the need to quantify uncertainties in often-used satellite products (particularly monthly mean composites) as well as the need to have a sufficient number of observations to assure the fidelity of monthly means. Additional work has spun up in early 2015 on creating a Cyanobacteria Assessment Network (CyAN) with operational agencies include EPA, NOAA, USGS, and NASA. Cyanobacteria can cause harmful algal blooms (HABs), which have an impact on inland and coastal water quality. Because of this there is a need to mainstream satellite ocean color capabilities into U.S. water quality management decisions. HABs have a direct impact on health and welfare of human society, links to consequences of land use change for human societies, and their frequency and intensity can be a barometer for ecosystem change in a variable and changing climate. The CyAN project is funded by NASA for the 2015-2018 period. One final update to a major milestone is the completion of the draft Coastal CARbon Synthesis (CCARS) report in July 2015. The CCARS activity is part of a long-term U.S. coastal carbon budgeting effort, a collaboration between the Ocean Carbon and Biogeochemistry (OCB) Program and the North American Carbon Program (NACP) of the U.S. Global Change Research Program (USGCRP) that has been supported by NASA and NSF. The report presents a draft carbon budget to the community for final refinement, and development of a community plan for future research activities to improve understanding of carbon cycling in coastal waters. The report identifies major gaps in regional coastal ocean research and observational coverage, and develops core recommendations to prioritize coastal carbon cycle research needs.

Research under NASA’s Carbon Monitoring System (CMS) program continued to focus on using satellite and airborne remote sensing capabilities to prototype key data products to meet U.S. carbon monitoring, reporting, and verification (MRV) needs. NASA has established a program of record for a Carbon Monitoring System and incorporated this work and a budget line of $10M per year into its long-term operating plan. The CMS program uses satellite and airborne remote sensing capabilities to prototype key data products for carbon monitoring, reporting, and verification, with a focus on the atmosphere and terrestrial regions. In the past year, the Science Team meeting was preceded by a day-long symposium of studies where end users and researchers have successfully developed research agendas that provide decision makers with insight into state level (e.g., Maryland), regional terrestrial biomass estimates (Sonoma, CA) as well as Indonesia, Mexico and African carbon dynamics (<http://carbon.nasa.gov/>). Accomplishments to date include globally gridded land use and land cover projections to 2100 using remote sensing alongside land use allocations from a socio-economic model (West et al., 2014). Estimating carbon in African Mangroves and wetlands to prepare for REDD and Blue Carbon utilized WOrldView-a data as well as TanDEM-X Pol-InSAR inversions (publications by Lee and Fatoyinbo, 2015 and Lagomasino et al., 2015*)*. A high-resolution methane and carbon dioxide flux inventory was completed for the northeast corridor of the US (McKain et al., 2015; Gately et al., 2015).

During the past year additional new or improved satellite remote sensing data products and assessments have been developed and released. NASA has also funded research to prepare for new biological and chemical observations of land cover land use change, terrestrial ecology, ocean biology and biogeochemistry, and biodiversity from new suborbital and satellite missions. Examples of new data sets include one that describes long-term changes in forests from space. A team at the University of Maryland - College Park used Landsat and Corona data for mapping forest cover change from the mid-1960s to 2000s. This data set successfully extends the spatio-temporal coverage provided by the Landsat constellation further back to 1960’s to map forest cover in case studies over the Eastern United States  (urban) and Central Brazil (tropical forest). This effort revealed different forest cover change trajectories during 1960s and 2000s.

<http://www.sciencedirect.com/science/article/pii/S0924271614002305>.) Improvements to models and management-based data products have also been developed, including satellite-based daily global 5km products for the NOAA Coral Reef Watch (CRW) program.  Reef managers and researchers can use these products to monitor directly thermal stress on 95% of the world’s reefs.  These 5km products are an improvement over the heritage 50km products and make use of higher spatial resolution and higher data density sea surface temperature (SST) products and a new climatology.  The 5km products include SST Anomaly, Coral Bleaching HotSpots, Degree Heating Weeks, and Bleaching Alert Area (Liu et al., 2014).

Fundamental remote sensing research, algorithm development and refinement, and exploration of new methods also continue within the program. Select examples include MODIS–Landsat fusion for large area 30 m burned area mapping (Boschetti et al., 2015), as well as experimental products for harmful algal bloom mapping (Hu et al., 2015), wetlands (McCarthy et al., 2015), oil slicks (Hu et al., 2015), primary production (Lee et al., 2015), and ocean macroalgae from hyperspectral data (Hyperspectral Imager for the Coastal Ocean – Hu et al, in press). Advance planning for future research efforts also have continued for land and ocean, including the EXport Processes in the Ocean from RemoTe Sensing (EXPORTS). EXPORTS is a science plan for a future NASA field campaign to develop a predictive understanding of the export and fate of global ocean primary production and its implications for the Earth’s carbon cycle in present and future climates. NASA’s satellite ocean-color data record has revolutionized our understanding of global marine systems by providing synoptic and repeated global observations of phytoplankton stocks and rates of primary production. EXPORTS is designed to advance the utility of NASA ocean color assets to predict how changes in ocean primary production will impact the global carbon cycle. A Science Definition Team will be competed in summer 2015. Paired with this effort is the selection and first meeting of the Pre-Aerosol, Cloud, ocean Ecosystem mission (PACE) science team, focused on theoretical and analytical studies associated with inherent optical properties of the ocean and atmospheric correction. Improvements to the optical properties of the ocean and the atmospheric correction are critical to the execution of the science of the PACE mission, as well as to improvements of carbon properties of the ocean that are the goal of EXPORTS. The optical properties research funded under the PACE Science Team is also foundational work for retrievals of systematic and new observations of ocean properties from PACE, including phytoplankton and primary production. Finally, two reports defined advanced science plans for terrestrial ecosystem and carbon cycle-climate science**.** Two major workshops were convened to determine and prioritize measurements required to support research communities as well as scientific gaps and frameworks for (1) Terrestrial Ecosystem, Carbon cycle, Landcover/land Use change and Biodiversity (TECLUB); and (2) carbon and climate research communities. Both reports are in draft form and will be finalized in 2015.

The Multi-scale Terrestrial Model Intercomparison Project (MsTMIP) is leveraging an ensemble of terrestrial biospheric models (TBMs) run using a consistent protocol (Huntzinger et al. 2013) and driver data (Wei et al. 2014) to explore key questions in carbon cycle science. A series of standardized simulations makes it possible to understand the role of model structural differences in the uncertainties associated with key components of the carbon cycle. The bundled version of MsTMIP simulation results was released in March 2015 (Huntzinger et al. 2015). In the last year, Wei et al. (2014) published a manuscript describing the environmental driver data put together for MsTMIP. Tian et al. (2015) used MsTMIP results to assess global patterns of, and controls on, soil organic dynamics. Schwalm et al. (2015) assessed the degree to which weighted integration of model estimates compared to classical one-model-one-vote approaches. Mao et al (in press) explored the climatic and anthropogenic controls on global terrestrial evapotranspiration trends. Many additional studies are also under way.

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| FY 2015 Annual Performance Indicator | FY 12 | FY13 | FY14 | FY15 |
| **ES-15-6:** Demonstrate planned progress in detecting and predicting changes in Earth’s ecological and chemical cycles, including land cover, biodiversity, and the global carbon cycle. Progress relative to the objectives in NASA's 2014 Science Plan will be evaluated by external expert review. | Green | Green | Green | Green |

**Annual Performance Indicator ES-15-1: Demonstrate planned progress in advancing the understanding of changes in Earth’s radiation balance, air quality, and the ozone layer that result from changes in atmospheric composition.**

Over the past year, NASA researchers and partners involved with the Atmospheric Composition Focus Area (ACFA) have made gains in achieving the aforementioned mandate. These advances are presented along the following four general interest areas: 1) Stratosphere; 2) Tropospheric Ozone and Related Topics; 3) Aerosols (Smoke/Dust) Transports/Sources/Sinks; and 4) Aerosol and Cloud Radiative Properties. Highlights of note taken from a wide range of recently published papers provide an unprecedented view of the temporal and spatial distributions of air pollution and air quality both at home and abroad.

An emerging theme among this year’s published studies involves multi-year trends, sometimes longer than a decade, in the emissions of atmospheric trace gases emitted from regions experiencing rapid socio-environmental change. Geographic foci of scientific interest include central Asia, southern Africa, and the eastern U.S. as well as regions that experience extensive biomass burning such as South America, Indonesia, Australia and the forested Boreal zones. The key to the planned progress of these studies rests with the power of combining ground-based, in-situ and remote sensing observations supported by ACFA related programs.

The Focus Area continues to make use of an Earth Science Publications website established several years ago to track publications in a quantitative manner (<http://esdpubs.nasa.gov>). At least 152 atmospheric composition-relevant papers using NASA funding were uploaded to the ESD publications site during 2014-2015, including 38 papers during the first half of 2015.

**Programmatic Highlights:**

A major programmatic highlight for the ACFA was the release of the MODIS/Terra Collection 6 Aerosol, Cloud and other Atmospheric Level-2 and Level-3 products in April, 2015. The MODIS Atmosphere Team algorithm developers have released Terra Collection 6 (C6) reprocessing and forward processing product streams. New C6 Level-2 products include aerosol (MOD04\_L2, MOD04\_3K), cloud (MOD06\_L2), column water vapor (MOD05\_L2), and joint (MODATML2) sub-sampled products.  Additionally, global browse and Level-3 Terra C6 products have been released. MODIS/Terra C6 algorithms parallel the numerous improvements and data set changes that were reported previously for MODIS/Aqua C6. A complete description of algorithm changes and product details can be found in documents available at <http://modis-atmos.gsfc.nasa.gov/products_C006update.html>. Another programmatic highlight was the concluding SEAC4RS Science Team Meeting held at the California Institute of Technology from April 28 – May 1, 2015. Results from data analyses and modeling activities were presented. Furthermore, plans were made for additional, more synthetic work in the coming year.

**Highlights of findings related to changes in the composition of the stratosphere:**

An ACFA supported Chemistry-Climate-Model study found that the inter-hemispheric gradient (IHG) and the global trend provide useful information for quantitatively constraining carbon tetrachloride (CCl4) emissions and lifetime estimates (Liang et al. 2014). Yet another study reported that emissions of hydroflourocarbons (HFCs) from developed countries are consistent with atmospheric measurements, and almost half of global emissions now originate from non-reporting countries (Lunt et al. 2015). Another study found that satellite data analysis challenges previous views of stratospheric water vapor trends and calls into question previous estimates of surface radiative forcing based on presumed global long-term increases in water vapor concentrations in the lower stratosphere (Hegglin et al. 2014). The study uses an approach that aims to merge satellite data sets from the late 1980’s through to present with the help of a chemistry-climate-model.

Other findings include an explanation of the anamolous increase in stratospheric chlorine due to short-term dynamical variability (Mahieu et al. 2014). Another study found that with the use of MPLNET observations, researchers were able to reinterpret previous studies focused on the stratospheric impact of the Nabro and Sarychev volcanic aerosol plume transports as determined from Optical Spectrograph and Infrared Imaging System (OSIRIS) data and in the process provide yet another example of the importance of constraining remotely sensed observations with ground-based ones (Fromm et al. 2014).

**Highlights of findings related to changes in the composition of the troposphere:**

Recently published scientific results highlight how the use of satellite derived data, when combined with ground-based and in-situ observations, improves model estimates of ozone and its precursors both in the USA and abroad. Domestically, scientific results from the Earth Venture Suborbital program investigation DISCOVER-AQ (Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality) have found that for the Baltimore-Washington metropolitan area, emissions of NOx from mobile sources are overestimated by at least 50% in the National Emissions Inventory (Anderson et al. 2014). Results this study also indicate that ambient ozone concentrations will respond efficiently to NO*x* emissions controls but additional sources may need to be targeted for reductions. Internationally, Indian and southeastern Asian emissions of O3 pollution exported to the northwestern Pacific were found to be comparable to Chinese emissions in winter, ~ 50% of Chinese emissions in spring and fall, and approximately 20% of Chinese summer emissions (Jiang et al. 2015).

Studies of a more longitudinal nature also elucidated trends in two important atmospheric gases in the troposphere: ozone and carbon monoxide. One study published this year makes use of combined ground-based, in-situ and satellite observations found that over a seventeen-year period (1990 to 2007) there has been an increase in tropospheric ozone over southern Africa and that this may be a harbinger of conditions to come as socio-economic changes continue for the region (Thompson et al. 2014). Another study that uses observations from 2002 to 2011 from both the MOPITT instrument and in-situ measurements reported a decrease in the spatial distribution of tropospheric CO, thereby suggesting decreases in both fossil fuel and biofuel emissions over Europe, the USA and Asia as well as reductions in biomass burning emissions from South America, Indonesia, Australia and Boreal regions (Yin et al. 2015). These seemingly divergent results highlight the need to continue to investigate changes in atmospheric composition at regional scales and then relating these changes larger temporal and spatial scales (i.e., from satellites).

Also of note was the 2015 Huang et al. study that used observations during the ARCTAS campaign of 2008 to identify and account for negative biases in GEOS-CHEM simulations. Huang et al. went on to assimilate AURA TES observations into their study and improved the predictive skill of the models as validated against ARCTAS observations. This also resulted in improved background ozone estimates for the western U.S.

**Highlights of improved understandings of aerosol sources, transports and sinks:**

Provocative findings regarding the role of biomass burning emissions and severe weather in the U.S. were put forth by Saide et al. (2015) who posited that biomass burning emissions transported from central America provided an environment to enhance the development of tornados in the U.S. Their main assertion is that transporting biomass burning emissions into an atmospheric environment that is already conducive to severe thunderstorm development can increase the probability of tornado genesis by modifying the atmospheric profiles of clouds and low-level shear.

Findings from two studies this year both better constrained the transport and deposition of Saharan dust to the Amazon Basin using satellite CALIOP data. Yu et al. (2015a,b) both improved estimates of trans-Atlantic Saharan dust transport and supported the hypothesis that Saharan dust transport from northern Africa helps to maintain the supply of phosphorus to the Amazon Basin.

Another biomass burning study that used satellite observations reveals substantial burning during the 2007 and 2010 tropical South America fire season, with both years exhibiting similar total burned area (Bloom et al. 2014). However, the reported 2010 CO fire emissions estimated from satellite data were substantially lower (−28%), despite this being a once-in-a-century drought year.

**Highlights of improved understanding of aerosol cloud interactions and resultant radiative properties associated with changes in atmospheric composition:**

Along similar lines as those put forth by Saide et al. (2015), a study using ground-based (AERONET and MPLNET) and in-situ cloud microphysics information collected during the DISCOVER-AQ Baltimore-Washington campaign found rapid aerosol optical depth enhancements in the vicinity of polluted cumulus clouds implying possible new particle formation in addition to cloud processing and humidification of existing particles (Eck et al. 2014). These findings suggest that summertime cumulus clouds may at times significant modify the aerosol vertical profile, at least temporarily creating an enhanced aerosol layer in the upper half of the mixed layer.

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| FY2015 Annual Performance Indicator | FY 12 | FY13 | FY14 | FY15 |
| **ES-15-1:** Demonstrate planned progress in advancing the understanding of changes in Earth’s radiation balance, air quality, and the ozone layer that result from changes in atmospheric composition. Progress relative to the objectives in NASA's 2014 Science Plan will be evaluated by external expert review. | Green | Green | Green | Green |

**Annual Performance Indicator ES-15-9: Demonstrate planned progress in improving the ability to predict climate changes by better understanding the roles and interactions of the ocean, atmosphere, land, and ice in the climate system.**

The NASA Climate Variability and Change (CVC) Focus Area is composed of three programs which cover research on the physical oceanography, cryospheric sciences, and global modeling aspects of climate variability. NASA has an array of space assets that measure different aspects of the ocean, cryosphere , and atmosphere. These include satellite observations ranging from sea surface height, salinity (until June 2015), temperature, ocean surface wind vectors, sea ice extent to glacial mass and shape, cloud properties, and vegetation cover. We highlight here some of the new results arising from the ongoing satellite observations and then discuss some of the integrative Earth System Modeling (ESM) results.

**Sea Level** change is one of the most tangible consequences of climate change, one with immediate societal consequences. NASA has a variety of assets to measure both the causes and amount of sea level change, such as the Jason-2 altimetric mission to measure the spatial distribution of sea surface height (continuing previous missions yielding a 22 year series), the Icebridge airborne mission to measure the change in volume of the Greenland and Antarctic ice sheets, the GRACE satellite pair to measure the mass change in Greenland, Antarctica and glaciers such as those in Alaska or the Himalayas, as well as the mass addition to the oceans, and NASA’s geodetic network (laser satellite tracking and GPS) to give the vertical position of satellites such as the upcoming Jason-3 or Icesat-2, or the in-situ tide gauges that have been measuring sea level for decades, to within a few centimeters. NASA selected an interdisciplinary Sea Level Change Science team covering the most important scientific aspects of sea level change: land hydrology, oceanography, cryospheric science and geodesy. This research team is expected to deliver integrative studies of sea level over the next 2-3 years.

A study of sea level rise using Jason-2 altimetry, GRACE and Argo floats concluded that the deep ocean has not warmed enough to account for the ‘hiatus’ in air temperature over the past decade, thus the added heat is stored in the upper layers of the ocean. The study finds that the total ocean warming (surface to bottom) between January 2005 and December 2013 is equivalent to a radiative imbalance of 0.64 +/- 0.44 W/m2 (Llovel et al 2014). Another study used sea level data to provide a strong constraint on climate models. It was found that the partitioning of northern and southern hemispheric simulated sea surface height changes from climate models are consistent with precise altimeter observations, but inconsistent with in-situ estimates of ocean heat content between 1970 and 2004, mostly associated with uncertainties in Southern Hemisphere data (Durack et al 2014).

There has been considerable discussion in recent literature about the effect of climate change on winds and ocean transport in the Southern Ocean. Large-scale climate models predict a poleward movement and strengthening of the westerly winds over the Southern Ocean in a warming world plus depletion of polar stratospheric ozone. These effects lead to increased ocean transport and a southward shift of the Antarctic Circumpolar Current (ACC) in climate models but not in high-resolution, eddy-resolving ocean-only models. Recently zonal (East-West) geostrophic velocity fields in the Southern Ocean were estimated from 2004 into 2011 based on sea level data from precise altimetry (Jason) and other data. It was discovered that the variability in the current in the Indian Ocean correlates with Southern Hemisphere winds as represented by the Antarctic Oscillation (Kosempa and Chambers 2014)).

Mesoscale eddies with spatial scales of order 100 km are ubiquitous features of the World Ocean, occupying ∼25% of the ocean's surface area at any given time. Eddies are the storms of the ocean, and transport heat, nutrients, and plankton. Over the past decade is has become clear that the best tool to detect individual eddies is their sea surface signal as measured by precise satellite radar altimetry (Jason-2 and the upcoming Jason-3). Recent work has found the observed chlorophyll response to eddies is consistent with the various theoretical mechanisms by which eddies influence phytoplankton communities (Gaube et al 2014).

Near real-time altimetry data are used by many offshore operations including offshore oil and gas exploration and production, oil spill and marine debris tracking, ﬁsheries industry and management, and ocean habitat monitoring. This includes assimilation of near real time sea surface height observations into ocean forecast models used by both the US Navy and NOAA. Because the slope of the sea surface is related to surface currents, these observations strongly constrain the forecasts. One example of operational application of altimetry data is the ongoing computation of Tropical Cyclone Heat Potential for the tropical Atlantic and Gulf of Mexico (at:

http://www.aoml.noaa.gov/phod/cyclone/data/)

**Ocean surface winds** (speed and direction) are one of two driving forces of ocean circulation, and also reflect the strength of tropical cyclones. The recently launched Rapidscat mission will help clarify the diurnal cycle of ocean surface wind, as well as track cyclones for NOAA’s National Weather Service. Rapidscat is key in cross-calibrating data from several missions is crucial to obtain a multi-decade climate data record of ocean winds for climate studies. In the last year the transfer of Ku-band standard from Quikscat to Rapidscat has been demonstrated.

The interaction of sea surface temperature with overlying winds has become an important topic of research over the past few years. Positive correlations of local surface wind anomalies with sea surface temperature (SST) anomalies at oceanic mesoscales (10–1000 km) suggest that the ocean influences atmospheric surface winds at these relatively small scales. This is in contrast to the negative correlations found at larger scales in midlatitudes that are interpreted as the atmosphere forcing the ocean through wind-driven modulation of surface heat fluxes and ocean mixed layer entrainment. A key result used Quikscat wind data together with sea surface temperature data from NASA’s infrared and microwave sensors to improve the parameterization of this effect in numerical atmospheric and coupled ocean-atmosphere numerical models, by investigating the physical causes of the correlation (Perlin et al. 2014).

**Sea Surface salinity** (SSS) links the ocean and its circulation with different elements of the water cycle such as evaporation and precipitation over the oceans, river runoff, and ice melt, and with elements of climate variability such as monsoons and El Niño/Southern Oscillation (ENSO). The impact of combined Aquarius and in-situ sea surface salinity (SSS) on El Nino forecasts has been demonstrated using a coupled ocean-atmosphere model for August 2011 until February 2014, and predicting “Niño 3 sea surface temperature”, a sensitive index of El Niño events. Assimilating Aquarius SSS prior to the data-free forecasting run gave significant improvement over the baseline for all forecast lead times after 5 months. A final experiment that uses subsampled Aquarius at locations where in-situ temperature data exist, infers that the high-density spatial sampling of Aquarius is the reason for the superior performance of Aquarius versus in situ SSS (Hackert et al. 2014).

**Sea surface temperature** (SST) is measured by NASA’s MODIS instruments in the infrared and by NASA’s GPM microwave imager in the microwave (following from the very successful TRMM microwave imager, as well as AMSR-E). As is evident in the previous paragraphs, SST is central to many studies, whether of sea surface height, wind or salinity. Scientists have reported the existence of mesoscale multiple zonal jets in the World Ocean, both globally and regionally. They are referred to as quasi-zonal because they departure from a strictly zonal orientation and latent owing to their order 1 cm/s magnitude relative to the more dominant order 10 cm/s eddy field. The currents alternate in direction and are nominally separated by 200 km, and were first identified in sea surface height. Various theories have been proposed to explain the existence of such jets, involving both the Earth’s rotation and cascades of energy from short to long scales as eddies interact. Recent work explored the existence of similar structures in sea surface temperature (SST) from AMSR-E data and found support for the view that propagating eddies help give rise to the bands (Buckingham et al. 2014).

Satellite data during the past year reinforced the long-term downward trend in **Arctic sea ice extent**. The September 2014 seasonal minimum extent was the sixth lowest on record, but more significantly, the seasonal maximum extent was achieved 15 days earlier than the long-term average, pushing it into February 2015, and was the lowest in the satellite record. A combination of data from submarine-, helicopter-, aircraft-, and satellite-based sensors revealed a trend in annual mean ice thickness across the Arctic Basin of −0.58 ± 0.07 m per decade over the period 2000–2012. Around Antarctica, sea ice reached a record high extent in September 2014, exceeding 20 million square kilometers for the first time in the satellite record. Each of the last three years has set new record highs for maximum extent in the Southern Ocean. The global annual sea ice cycle is dominated by the high-amplitude Antarctic annual cycle, but its trend is more in line with the high-magnitude negative Arctic trends.

Our picture of the **Greenland Ice Sheet** continues to develop, with more information than ever about its surface and the bedrock beneath it. Aircraft and satellite laser altimetry measurements from 1993-2012 have been compiled to reconstruct records of ice thickness change at 100,000 sites in Greenland. Most outlet glaciers have been thinning during the last two decades, interrupted by episodes of decreasing thinning or even thickening. Dynamics of the major outlet glaciers have dominated the mass loss from larger drainage basins, but the intricate spatiotemporal pattern of dynamic thickness change suggests that the response of individual glaciers is modulated by local conditions. This suggests that recent extrapolations from four major outlet glaciers may not accurately represent conditions around the ice sheet periphery (Csatho et al. 2014). A comprehensive deep radiostratigraphy of the Greenland Ice Sheet has been constructed from airborne ice-penetrating radar data collected between 1993 and 2013. New techniques for predicting reflection slope from the phase recorded by coherent radars were developed, that when integrated along track, simplify semiautomatic reflection tracing. The resulting radiostratigraphy provides a new constraint on the dynamics and history of the ice sheet (Macgregor et al. 2015).

The role of water in the evolution of the Greenland Ice Sheet has been quantified using high-resolution commercial satellite imagery and in situ measurements. After the record surface melt event in 2012, efficient surface drainage was routed through 523 high-order stream/river channel networks, all of which terminated in moulins (vertical conduits connecting the surface and base of the ice sheet) before reaching the ice edge. This suggests that the interior of the ice sheet can be efficiently drained under optimal conditions. The introduction of meltwater to the bed through neighboring moulin systems produces ice-sheet uplift and/or enhanced basal slip, enhancing the propagation of fractures beneath supraglacial (surface) lakes. In less crevassed regions, such as the interior of the ice sheet, where water at the bed is currently less pervasive, the creation of new surface-to-bed conduits caused by lake-draining hydro-fractures may be limited (Smith et al. 2015).

**Antarctic Ice shelves** are key to restraining the flow of grounded ice around the continent. As ice shelves thin, their ability to buttress the grounded ice diminishes. Eighteen years of continuous satellite radar altimeter observations have been compiled to discern decadal-scale changes in the thicknesses of the ice shelves around Antarctica. Overall, average ice-shelf volume change accelerated from a negligible loss of 25 +/– 64 cubic kilometers per year for 1994-2003 to a rapid loss of 310+/–74 cubic kilometers per year for 2003–2012. Recent observations from Operation IceBridge altimetry and InSAR-inferred ice flow speeds suggest that the remnant Larsen B ice shelf is no longer able to buttress its tributary glaciers. Numerical modeling and data assimilation show that the observed dynamic thinning is accompanied by a weakening of the shear zones between its flow units and an increase in its fracture. Combined with the retreat of the ice front, the flow acceleration and enhanced fracture signal the impending demise of the surviving ice shelf (Paolo et al. 2015).

The NASA **Modeling, Analysis, and Prediction** (MAP) program is focused on the development and utilization of comprehensive, interactive models of the Earth system, incorporating both the faster components of the climate system (atmosphere, land surface, vegetation) and slower components (oceans, cryosphere) into models which will allow investigation of the relative roles of these components in the Earth system and confident prediction of future states of the Earth system from weather to centennial time scales. The MAP program includes the production of a best-effort analysis of the Earth's current meteorological state, numerical weather prediction, and reanalyses. A significant result of the reanalysis effort was the development of an update to the very successful Modern Era Reanalysis for Research and Applications (MERRA), known as MERRA2. The reanalysis uses an updated data analysis system and model, and incorporates more recent observations. It will be released to the public in August of 2015 and will be available at: http://gmao.gsfc.nasa.gov/products/.

To further our ability to evaluate the **design and impact of new observations in models**, a very high resolution (7 km) "Nature Run," was completed and will become a central component of Observing System Simulation Experiments. The new Nature Run includes 2 years of simulation at 7 km, is non-hydrostatic, and includes aerosols and tracer species (<http://www.nasa.gov/press/goddard/2014/november/nasa-computer-model-provides-a-new-portrait-of-carbon-dioxide/index.html#.VagH5kivwkr>)

The diurnal cycle of upper tropospheric **ice clouds** simulated by the GISS Model E and a number of other Earth system models were compared with observations from the Superconducting Submillimeter Limb Emission Sounder (SMILES) instrument, which flies on the International Space Station. A large variation in the model diurnal cycles was discovered, indicating that the physical mechanisms governing the diurnal cycle of ice clouds are not well represented in current climate models (Jiang et al. 2015).

The capability to include **vegetation** in NASA ESMs was improved this year with the development of high-resolution daily vegetation composites from the MODIS satellite over the continental United States. This new composite, which has daily temporal resolution at a one-kilometer geographic resolution, is a significant improvement over the monthly, sixteen-kilometer vegetation composite that it replaces (Case et al. 2014).

To create as **comprehensive a modeling system** as possible, external partnering with NASA ESM is extensive. A significant advance was made in the coupling of the GEOS 5 Data Assimilation System (DAS) and Earth System Model with the Harvard GEOS-Chem Chemistry and Transport Model (CTM), traditionally a stand-alone CTM driven using meteorological fields from the GEOS5 DAS. A single-column version of the GEOS-Chem model was developed and incorporated into the GEOS 5 DAS. This allows on-line runs of the GEOS-Chem, chemical data assimilation, and importantly provides a mechanism whereby the GEOS-Chem standalone and GEOS-Chem inline codes are constantly updated and kept consistent. Since GEOS-Chem is developed and used by a large number of university investigators, incorporating GEOS-Chem allows NASA to leverage the work of this large community and maintain and run a model with the most up-to-date set of tropospheric chemical processes available. The work was made possible using the NASA MAP-funded Earth System Modeling Framework, which provided standardized computational interfaces between the GEOS-Chem and GEOS 5 codes. Also developed this year is a complementary emissions module to be used with the online version of GEOS-Chem (Long et al. 2015).

Also incorporated into the GEOS 5 ESM model this year for the first time is the University of Wyoming-developed "Modal Aerosol Module (version 7)," which provides a description of aerosols complete enough to allow for studies of aerosol indirect effect on clouds, but not so complicated that running the model is computationally infeasible.

The GEOS-5 GCM, when combined with appropriate modules for representing Atmospheric chemistry, becomes the GEOS-CCM (GEOS Chemistry Climate Model). This year, a simplified parameterization of methane chemistry was implemented successfully in the GEOS-CCM. This parameterization will enable longer-term studies of the climate impact of methane, and in particular how methane could act as a positive feedback in a warming atmosphere forced by increases in CO2 through the release of methane from wetlands reservoirs.

The GISS Model E Earth System Model/General Circulation Model is a second large-scale GCM/ESM designed for investigations of climate variability and change on up to centennial timescales. Development continued this year, with implementation of gravity waves associated with model convection and increased vertical resolution resulted for the first time in the generation of a realistic stratospheric quasi-biennial oscillation (QBO) by the model. The QBO was created in versions of the Model E code that extend above the stratosphere. This allows more realistic simulations of the Earth's middle atmosphere, including effects of the stratosphere on the troposphere (Rind et al. 2014). The Model E was improved in other ways as well this year. The convective parameterization, which was previously updated to include a parameterization of cold pools, has been found to substantially improve the representation of the Madden-Julian Oscillation. The MJO is one of the most significant short-term climate fluctuations and improving its representation may have a strong influence on the model's skill in climate prediction on subseasonal time scales (Del Genio et al. 2015).

An important **ocean modeling**-related result was a proposed mechanism for the observed asymmetric warming of the Arctic compared to the Antarctic during the industrial period. The asymmetry has been tied to the characteristic mean ocean circulation; upwelling cold water in the Antarctic should strongly suppress sea-surface temperature increases in the Antarctic, whereas this does not occur in the Arctic with its characteristic downwelling currents, allowing more rapid arctic warming (Marshall et al. 2014).

A major **atmosphere modeling**-related result component was the determination of the mechanism surrounding observed increases in tropical rainfall over the last 30 years. Most of the observed increase in tropical precipitation is caused by increases in the occurrence of large, well-organized, intense storm systems. Alternative explanations, such as precipitation changes in disorganized deep convective systems or increases in the amount of rainfall occurring in organized deep convective systems do not fit the observations. These results provide a goal for continued climate model development, which do not currently represent these processes well (Tan et al. 2015)

Proper representation of **tropical cyclones in climate models** depends partly on having sufficiently high model resolution to adequately resolve the cyclones. The recent improvement in the GISS Model E resolution to 1-degree longitude by 1-degree latitude provided an opportunity to evaluate the representativeness of the tropical cyclones it generates at this resolution. Compared to observations, the model produced a reasonable simulation. Perhaps more important in this study however, was the investigation and discovery of the response of the cyclones to independent increases in sea surface temperatures and carbon dioxide concentrations. Modeled responses to these two forcings were of the same size and opposite in effect, which together resulted in only a small model sensitivity to the combination. This result suggests that tropical cyclones may respond only weakly to the Earth's global warming over the coming century (Shaevitz et al 2014).

Accurately representing **precipitation** presents another challenge to the models. This year progress was made in developing a more comprehensive picture of clouds and their characteristic radiative and hydrologic properties. A clustering analysis of joint histograms of cloud top pressure and optical thickness revealed that cloud "regimes" could be defined, and that such a definition would provide a useful metric for evaluation of modeled clouds, including the tie to radiative and hydrologic properties (Oreopoulos et al. 2014).

A study of **climate forcing** demonstrated that irrigation constitutes a small but significant source of anthropogenic climate forcing, which tends to have a cooling effect. The cooling has a substantial regional variation. Another relatively poorly studied source of climate forcing is the impact of dust, black carbon and organic carbon which darkens snow surfaces in some locations around the world. A MAP-funded study showed that snow darkening causes substantial regional climate forcing, suggesting that higher resolution climate models will need to include such effects to correctly represent regional variations in climate. The uneven distribution of historical aerosol, ozone, and land use forcing was also found this year to result in large impacts on regional-scale temperature response to the forcing. This contrasts with the more uniform forcing produced by well-mixed greenhouse gases (Cook et al. 2015).

Modeling **stratospheric chemistry/climate interactions** made significant advances. The observational record of stratospheric ozone has become long enough and spanned enough local times to allow a statistically robust reconstruction of its diurnal cycle, which was compared to GEOS-CCM simulations. Also studied was the possible effect of geoengineering on the stratospheric QBO. Model studies found a large impact on the simulated QBO following an injection of sulfate aerosol into the stratosphere, one of the primary geoengineering strategies envisioned to increase scattering of solar radiation and reduce greenhouse-gas driven surface temperature increases. Finally, variability of inorganic chlorine in the Antarctic stratospheric polar vortex and its implications was examined. The observed large variability in inorganic chlorine complicates attribution of ozone recovery to changes in chlorine, and implies that at least 10 years of measurements will be needed to establish a statistically robust relationship (Aquila et al. 2014).

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**Annual Performance Indicator ES-15-11: Demonstrate planned progress in characterizing the dynamics of Earth’s surface and interior, improving the capability to assess and respond to natural hazards and extreme events.**

NASA’s Earth Surface and Interior focus area (ESI) continues to advance the understanding of core, mantle, and lithospheric structure and dynamics, and interactions between these processes and Earth’s fluid envelopes. Research conducted in the past year has also provided the basic understanding and data products needed to inform the assessment and mitigation of natural hazards, including earthquakes, tsunamis, landslides, and volcanic eruptions. ESI’s Space Geodesy Program (SGP) continues to produce observations that refine our knowledge of Earth’s shape, rotation, orientation, and gravity, foundational to many Earth missions and location-based observations. Highlights of research and accomplishments of the past year are summarized below.

**Natural Hazards Research**

NASA realized a number of significant scientific advancements this year in understanding geohazards including earthquakes, volcanoes, landslides, land subsidence, and tsunami. Significant events included the South Napa Earthquake in Northern California, volcanic unrest at Copahue volcano in Argentina, the eruptions of Turrialba in Costa Rica and Villarrica in Chile, and the magnitude 7.8 Gorkha Earthquake and its secondary hazards in Nepal. NASA took a proactive role with each of these events with tasking, processing, analysis, and/or the distribution of products to the both the scientific and response communities.

The Advanced Rapid Imaging and Analysis project (ARIA) is a joint JPL/Caltech effort to automate SAR and GPS imaging capabilities for scientific understanding, hazard response, and societal benefit. Over the past year, the ARIA team has been building on its prototype data system to increase its operational analysis capabilities and directly provided rapid response geodetic data and imagery to many natural hazard events around the globe. The Real-time Earthquake Analysis for Disaster (READI) Mitigation Network Working Group (WG) is an umbrella for several NASA-funded projects that focus on earthquake and tsunami early warning systems and rapid response in the western U.S. Both ARIA and READI led research responses to significant solid-Earth events of the past year.

ARIA mobilized following the August 24, 2014 magnitude 6.0 South Napa Earthquake. NASA-derived interferograms were widely used by local, state, academic and federal geologists and engineers to identify and measure fault slip across the complex Napa fault zone and assess if the mainshock damaged nearby levees and infrastructure. The team analyzed the coseismic and postseismic deformation with a cross-platform time-series analysis of the COSMO-SkyMed (CSK), Sentinel-1 InSAR, UAVSAR, RADARSAT-2, and GPS data. Results of a coseismic slip model derived from a slip inversion of reprocessed CSK and Sentinel-1 interferograms combined with GPS coseismic offset estimates found that the distribution of the maximum slip on the fault surface was shallower on the northern part of the rupture and deeper at the southern section rupture (Barnhart et al., 2015). This resulted in a “slip deficit” on the shallow southern section of the fault. Postseismic afterslip was almost entirely concentrated in this shallow southern part of the fault and may have accommodated some of the “slip deficit”. UAVSAR imagery was used extensively to map the mosaic of triggered fault segments and assess their relationship to the main fault strands. The READI project combined GPS and seismic data to resolve a dipping strike-slip mechanism for the mainshock as part of the rapid response (Melgar et al., 2015).

ESI research also played a major role in coordinating the scientific research response to the April 25, 2015 magnitude 7.8 Gorkha Earthquake in Nepal. In collaboration with the Natural Disasters Application Area; USGS, NSF, USAID, and NGA; and international partners including JAXA, ESA, ISRO, CSA, and CEOS; ESI facilitated data collection, processing and distribution of research products. Specifically, ESI collaborated with NSF to support UNAVCO in retrieval of data from continuous GPS sites in the epicentral region that were at risk of being lost due to compromised telemetry. These data are instrumental for determining the extent and time evolution of the rupture during the main event, as well as monitoring aftershocks and postseismic deformation. The Gorkha Earthquake is likely the most geodetically data-rich low-angle thrust earthquake ever, thereby providing a unique opportunity to understand similarities and differences in the fundamental physics, deformation styles, and mechanisms associated with their offshore subduction zone counterparts. All GPS data acquired as part of this effort are accessible to the community with no latency via the UNAVCO website, and high-impact science publications are currently in review.

READI also further advanced tsunami-warning research. In cooperation with the Natural Disasters Application Area, ESI partners entered initial discussions on an Indo-Pacific earthquake and tsunami early warning system that leverages existing ESI GNSS data-service investments. This NASA effort is a collaboration with the State Department and NOAA to promote the sharing of real-time GNSS data within the Indo-Pacific nations through the Asia-Pacific Economic Cooperation (APEC), with emphasis on hazard assessment.This year, READI integrated seismogeodetic data, near shore tsunami wave observations by GPS buoys, and ocean-bottom pressure sensors and demonstrated significant improvements in kinematic fault slip modeling and tsunami predictions, for analysis of the 2011 Mw 9.0 Tohoku-Oki earthquake, Japan (Melgar and Bock, 2015). Scripps is also analyzing and posting 1 Hz GNSS data for about 90 stations within the western U.S., and the Central Washington University (CWU) READI group is now processing real-time GNSS for about 70 stations and is working to produce a combined Scripps-CWU real-time solution.

This past year also provided a number of results and new research opportunities in volcanic processes. UAVSAR and satellite InSAR imagery collected between of 2013 and 2014 at the Laguna del Maule caldera in the southern Andes of Chile shows that the broader volcanic complex (~15 km diameter) inflated 15-20 cm/yr between 2013-2014 (Le Mével et al., 2015). Lundgren et al. (2015) established a baseline of steady inflation at 3–4 cm/yr of Nevado del Ruiz since 2012 based on RADARSAT-2 satellite data, and identified a compressive regional stress that suggests dikes propagating from the source should become trapped in sills, possibly explaining the significant lateral separation of the source and Nevado del Ruiz Volcano. Early Spring of 2015 represented the third and final set of UAVSAR flights to Central and South America to collect data over a wide variety of targets, including a number of volcanoes. Both Turrialba in Costa Rica and Villarrica in Chile erupted during the flight campaign. UAVSAR imagery collected over the Galapagos hotspot volcano Sierra Negra shows a provisional ~1 meter of uplift between 2013-15. Analysis and computer modeling is currently underway with UAVSAR, satellite InSAR, and GPS data (where available) at a number of actively deforming Latin American volcanoes including Nevado del Ruiz, Cerro Negro, Copahue, and Calbuco, as wells as several volcanoes in Iceland that were collected in early summer 2015.

**Lithospheric Processes**

Lithospheric structure and dynamics, and interactions between these processes and the oceans, hydrologic system, and atmosphere are critical to understanding the Earth system. This includes the motion and rotation of tectonic plates, elastic properties of the crust and mantle, and the effects of surface loading resulting from surface water, ground water, other fluids, glaciers, and ice sheets. These studies also represent enabling research for the hazards advancements described above.

Characterization of the spatial, temporal, and depth variability of slip on subduction zone interfaces has made great strides in the past decade beginning with the discovery of slow slip events lasting from days to weeks using continuous GPS networks. A number of ESI studies further advanced understanding of these and other subduction processes, while improving analytical methods for capturing subtle interseismic signals along with large-scale co-seismic motion. Liu et al (2015) examined the space-time relationship between geodetically determined slow slip transients and seismically-observed low frequency earthquakes (LFEs) and very-low frequency earthquakes (V-LFEs) near the Nankai trough. They found a strong but distinct temporal correlation between transient slip and LFEs and V-LFEs, suggesting a different relationship to the SSE and caution in using the seismically determined slow earthquakes as a proxy for slow slip. Xue et al. (2015) used a joint inversion of InSAR and GPS data to resolve interseismic coupling beneath the Nicoya Peninsula, Costa Rica and found three strongly coupled patches. Two patches correlate with recent earthquakes and the third patch is in a transition zone between an area of known slow slip events and earthquakes. Furthermore, they demonstrated that InSAR data can be used to recover small long-wavelength deformation signals with refined resolution in challenging subduction zone environments when integrated with GPS time-series.

Three studies in California combined SAR, GPS, seismic, and other data to better resolve and understand interactions between hydraulic systems and solid-Earth deformation. Chaussard et al. (2014) analyzed the deep archive of satellite InSAR acquired by the European Space Agency ERS-1, ERS-2, and Envisat satellites and JAXA ALOS satellite for the San Francisco Bay Area. Their research characterized the surface deformation caused by ground water storage variations and the predictability of hydraulic head changes in the San Jose area (Santa Clara Valley) between 1992–2011. Farr and Liu (2015) integrated multiple geodetic data sources and found a region within the Central valley subsiding at a rate of ~10 cm/yr. InSAR interferograms, GPS, and groundwater level time-series track well, matching seasonal surface elevation with withdrawals. Wei et al. (2015) investigated an earthquake swarm in the vicinity of fluid injection at the North Brawley Geothermal Field. Jointly analysis of broadband and strong motion waveforms, UAVSAR, leveling measurements and field observations suggest that the 2012 earthquake sequence was preceded by aseismic slip on a shallow normal fault beneath the geothermal field and was induced indirectly by fluid injection.

**Deep-Earth Processes**

The dynamics of the mantle and core fundamentally drive the evolution of the Earth’s shape, its orientation and rotation, plate motions and deformation, and the generation of the magnetic field. Research on the Earth’s interior utilizes gravity, topography, magnetic, or other geodetic methods and associated modeling and analysis to advance the understanding of the Earth’s deep interior and its interdependencies with the Earth system. Complete understanding of these global-scale processes requires the perspectives provided by space-based and other remote-sensing observations, and a number of advancements in this space were realized in the past year.

Currently, GPS and InSAR measurements are used to monitor deformation produced by slip on earthquake faults. It has been suggested that another method to accomplish many of the same objectives would be through satellite-based gravity measurements. Han et al. (2015) used over a decade of Gravity Recovery and Climate Experiment (GRACE) data to measure and model the large coseismic and postseismic gravity changes following seismic events. In particular, the 2012 Indian Ocean earthquake sequence (Mw 8.6, 8.2) is a rare example of great strike-slip earthquakes in an intraoceanic setting. An analysis using five moment tensor components and the approach of normal mode decomposition and spatial localization revealed that the gravity changes are produced predominantly by coseismic compression and dilatation within the oceanic crust and upper mantle and by postseismic vertical motion. These results suggest that the postseismic positive gravity and the postseismic uplift measured with GPS within the coseismic compressional quadrant are best fit by ongoing uplift associated with viscoelastic mantle relaxation. This demonstrates that GRACE data are suitable for analyzing strike-slip earthquakes as small as Mw 8.2 with the noise characteristics of this region. To further inform the potential for gravity missions to contribute to earthquake research, Schultz et al. (2014) used numerical simulations of earthquake fault systems to estimate gravity changes. The Virtual California (VC) model, which simulates faults of any orientation, dip, and rake, was used to explore the accuracies needed for such studies. Computed gravity changes are in the range of tens of μGal over distances up to a few hundred kilometers, near the detection threshold for GRACE.

Two studies considered joint GPS-GRACE datasets to inform deformation due to ice and hydrologic loading.Fu et al. (2015) found that GPS-inferred water storage variations in the Cascade Range were consistent with that derived from JPL's GRACE monthly mass grid solutions. The distribution of water variation inferred from GPS was found to be highly correlated with physiographic provinces in Washington and Oregon: the seasonal water is mostly located in the mountain areas, such as the Cascade Range and Olympic Mountains, and is much smaller in the basin and valley areas of the Columbia Basin and Harney Basin. These GPS-inferred water storage variations can determine and verify local scaling factors for GRACE measurements; in the Cascade Range, the RMS reduction between GRACE series scaled by GPS and scaled by the hydrological model-based GRACE Tellus gain factors is up to 90.5%. The study demonstrates that GPS-determined water storage variations can fill gaps in the current GRACE mission, as well as in the transition period from the current GRACE to the future GRACE Follow-on missions.

The ICE-6G\_C (VM5a) model of the last deglaciation event of the Late Quaternary ice age was released by Peltier et al. (2015), incorporating explicit refinements by applying all of the available GPS measurements of vertical motion of the crust that may be brought to bear to constrain the thickness of local ice cover as well as the timing of its removal. The study focused on North America, Northwestern Europe/Eurasia, and Antarctica. In each of the three major regions, the model predictions of the time rate of change of the gravitational field were compared to that measured by GRACE as an independent means of verifying the significant improvement of the model achieved by applying the GPS constraints. The study helped to confirm that misfits in vertical crustal motion can be mapped solely into modifications to glaciation history, as opposed to lateral heterogeneity of viscosity and/or lithospheric thickness.

ESI-supported members of the ESA-led Swarm Science Team released updated geomagnetic field models, continued calibration and validation efforts, and contributed to the production and release of the World Magnetic Model (WMM2015) and International Geomagnetic Reference Field (IGRF-12). Sabaka et al. (2015) released the comprehensive magnetic field model CM5, derived from CHAMP, Ørsted and SAC-C satellite and observatory hourly-means data from August 2000 to January 2013 using the NASA-derived Swarm Level-2 Comprehensive Inversion (CI) algorithm. CM5 provides a continuous description of the major magnetic fields in the near-Earth region over this time span, and its lithospheric, ionospheric, and oceanic M2 tidal constituents may be used as validation tools for future Swarm Level-2 products coming from the CI algorithm and other dedicated product algorithms.

Geomagnetic field model development efforts fed significant contributions WMM2015 and IGRF-12, both released December 2014. WMM2015 is the standard model used by the U.S. Department of Defense, the U.K. Ministry of Defence, the North Atlantic Treaty Organization (NATO) and the International Hydrographic Organization (IHO), for navigation, attitude and heading referencing systems using the geomagnetic field. It is also used widely in civilian navigation and heading systems. IGRF-12 is the latest version of a standard mathematical description of the Earth's main magnetic field that is used widely in studies of the Earth's deep interior, its crust and its ionosphere and magnetosphere.

**Space Geodesy Program**

SGP produces foundational geodetic data resources that have enabled many of the scientific advancements this year across geohazards and other enabling research areas. NASA is leveraging geodetic investments through active participation within the Global Geodetic Observing System (GGOS). Currently, the SGP supports over 20 active bilateral international agreements, enabling mutually beneficial exchanges of geodetic data, instrumentation, software, and personnel, and is having ongoing bilateral discussions this year with a number of new potential international partners including Norway (for a NASA-supplied SLR antenna) and Brazil (for a potential new geodetic core site). During the past year, in cooperation with many international partners, SGP continued to play a key role in establishing, maintaining, and operating global geodetic networks that include next-generation Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite System (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) stations.

This year in partnership with the United States Naval Observatory, NASA began implementation of a new broadband VLBI station at NASA’s Kōkeʻe Park Geophysical Observatory in Hawaii. The new VLBI station is scheduled to begin operations in early 2016. SGP also began site preparations and development of the new station instrumentation for the McDonald Observatory in Texas, selected last year as the new western US multi-technique geodetic site. NASA also supported the installation of a new Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS) station at the Goldstone Deep Space network site in California.

NASA’s Satellite Laser Ranging (SLR) network set a new annual record with over 57,000 satellite pass segments tracked in 2014. NASA’s Very Long Baseline Interferometry (VLBI) stations also continue to be among the most productive of the global VLBI network and participated in the Continuous VLBI (CONT14) campaign that acquired 302,115 observations using a network of 17 International VLBI Service (IVS) stations over 15 days. The Crustal Dynamics Data Information System (CDDIS), which distributes NASA’s geodetic data, currently archives over 12 Tbytes of Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite System (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) data, derived products, and ancillary information from a network of over 1500 sites in over 1000 locations around the world.

SGP’s ITRF Combination Center (ITRF CC) at JPL contributed a terrestrial reference frame solution to the 2014 International Earth Rotation and Reference Systems Service (IERS) ITRF realization process. The IERS has certified JPL as an ITRF Combination Center, one of only three worldwide and the only one in the US. The ITRF is critical to many NASA flight missions and science objectives including understanding the future impact of sea level change.

JPL further collaborated with CDDIS to make real-time data available from 155 sites as well as 37 product streams. These data are and will continue to contribute to rapid response research to improve our understanding of natural hazards, as described above.

**Geodetic Imaging**

ESI has significant requirements for synthetic aperture radar (SAR) and interferometric SAR (InSAR) data to meet research objectives. NASA collaborates and partners with other domestic and international agencies to acquire and disseminate SAR/InSAR data for research and operational purposes. For example, NASA provides both airborne and spaceborne SAR/InSAR data as a contribution to the EarthScope partnership with NSF and USGS. Access to data from both spaceborne SAR missions (e.g., ERS-1/2, ENVISAT, RADARSAT-1, ALOS PALSAR, and SeaSAT) as well as airborne data (e.g., AirSAR, UAVSAR, and AirMOSS) are provided via the NASA distributed active archive center (DAAC) at the Alaska Satellite Facility (ASF) in Fairbanks, Alaska, and at the WInSAR consortium supported by ESI in cooperation with UNAVCO and at JPL. These data are freely open and available for public access, except as restricted by some international data providers. SAR, InSAR and derived products are in strong demand and nearly all data are available for immediate online download. Discussions are ongoing with the European Space Agency (ESA) on hosting of the C-band Sentinel-1 data by NASA at ASF-DAAC and also with the Argentine Space Agency (CONAE) on possible future archive and distribution of the L-band SAOCOM data.

The NASA-ISRO Synthetic Aperture Radar (NISAR) Science Definition Team advanced its solid-Earth science mission of global observations of land surface deformation and applied science objectives related to disasters through September 2014, February 2015, and June 2015 meetings. Members of the SDT chaired and presented papers at an invited session entitled “New Frontiers in Ecosystem, Solid Earth, Cryosphere, and Natural Hazards” at Fall AGU 2014. This included a presentation from the Volcano Deformation Database Task Force, which is assessing how more frequent observations, and expected associated increases in observed deformation episodes, can lead to more informed correlations between deformation and volcanic eruptions.

The airborne UAVSAR provides temporal coverage, higher resolution, significantly better noise performance, and customized viewing geometries not available from spaceborne SAR. The UAVSAR project includes the L-band SAR flown on the NASA Gulfstream-III and also capable of flying on the Global Hawk. UAVSAR complements existing spaceborne SAR capabilities and provides a technology and science testbed for development and demonstration of the NISAR mission, now in Phase B. Major solid-Earth research deployments during the past year included studies of volcanic deformation in Central and South America, California plate boundaries, Gulf Coast subsidence, and landslide mechanics study in Slumgullion, Colorado, some of which were described above.

In the past year the 1 arc-second Digital Elevation Model **(**DEM) generated from NASA’s Shuttle Radar Topography Mission (SRTM) has been released for all regions except for the Middle East, and complete release is planned by the end of the year. This will provide a consistent topographic base that can expand SAR and InSAR processing to areas with previously limited topographic coverage. Two versions of the 1 arc-second DEM – one developed by the National Geospatial Intelligence Agency (available through the US Geological Survey), and another by the California Institute of Technology’s Jet Propulsion Laboratory (available through NASA’s Land Processes Distributed Active Archive Center). The DEM is distributed as 1° by 1° “tiles,” with over 3.2 million tiles having been distributed through May 31, 2015.

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| FY 2015 Annual Performance Indicator | FY 12 | FY13 | FY14 | FY15 |
| ES-15-11: Demonstrate planned progress in characterizing the dynamics of Earth’s surface and interior, improving the capability to assess and respond to natural hazards and extreme events. Progress relative to the objectives in NASA's 2014 Science Plan will be evaluated by external expert review. | Green | Green | Green | Green |

**Annual Performance Indicator ES-15-3: Demonstrate planned progress in improving the capability to predict weather and extreme weather events.**

During fiscal year 2015 NASA sponsored research continued to gain new insight into weather and extreme-weather events by the utilization of data obtained from a variety of satellite platforms (GOES, TRMM, GPM, Aqua, Terra, Suomi-NPP, CloudSat, and CALIPSO), a hurricane field experiment, and a field experiment focusing on the technology in measuring 3-D winds. Some highlights of 2015 mentioned here include the successful collaboration between NASA’s SPoRT facility with NOAA NESDIS on the assessment of a new snowfall rate (SFR) product for use by forecast offices. NASA’s GMAO produced a very important ‘nature run” with 7 km resolution for use in testing the impact of potential future satellite observations for weather prediction. Also highlighted is the successful launch of the early operations f the Global Precipitation Mission that is beginning to deliver insight into precipitation structures and extremes, as well as the successful deployment of airborne wind lidars designed to test new technologies for eventual use on satellite platforms. Observations of three-dimensional winds continue to be the focus area of for improved forecasts. NASA also held a weather focus area workshop to solicit input from key stakeholders as part of the advanced planning process. To explore the fast convective processes in the atmosphere, NASA issued a ROSES element in 2015 on severe storm to seek insights into severe storm initiation, morphology and dynamics.

NASA’s primary investment is **transitioning weather research products from its satellite fleet into NOAA’s forecast offices** is the Short-term Prediction Research and Prediction (SPoRT) program which continued to make significant progress this year. The motivation for the SPoRT program focus is not only to demonstrate the direct societal benefit of NASA research satellites but also to support the use of these products by the operational weather community. In this performance period, SPoRT collaborated with NOAA NESDIS on an assessment of a snowfall rate (SFR) product that includes data from the Suomi-NPP Advanced Technology Microwave Sounder (ATMS) instrument.  ATMS provides more channels, better resolution, and a wider swath than previous operational microwave sounders, such as the Advanced Microwave Sounding Unit (AMSU) and Microwave Humidity Sounder (MHS).  The SFR product uses information in microwave channels to estimate liquid-equivalent snowfall rates that forecaster can use for pinpointing the locations of the heaviest snowfall during winter weather events.  These observations are being provided in near-real-time (less than 30 minutes latency) through access to data from direct broadcast provided by the University of Wisconsin/CIMSS.

During the historical northeast blizzard on January 27, 2015, using the Suomi-NPP ATMS SFR product, SPoRT was able to demonstrate heaviest snowfall at that time was centered over southeastern Connecticut with rates from 1-1.5 inches of snow per hour. Coupled with other microwave sensors on board other NOAA and European satellites, up to 10 swaths of observations were available to provide observations of where the heaviest snowfall was falling and allows forecasters to track these features when used in conjunction with GOES imagery and radar.

A graduate student at SPoRT provided near real time imaging for disaster monitor and relief efforts after a tornado outbreak event in Illinois. The student obtained the Landsat 8 imagery and disseminated through a tweet. The imagery was provided to SPoRT’s NWS partners shortly through the Applied Sciences’ Disasters project, made available through the “beta” version of the NOAA/NWS Damage Assessment Toolkit. The imagery helped provide additional continuity and clarity of the tornado’s track among the locations surveyed.

SPoRT also engaged in the use of new computing technologies. In a paper published during this performance period, researcher Andrew Molthan and colleagues (2014), reported in BAMS, the ability to perform timely numerical weather prediction model forecast using cloud computing resources that are rapidly-expanding within the public-private sector.

Special emphasis was given to developing countries that may have limited access to traditional supercomputing facilities. Amazon Elastic Compute Cloud (EC2) resources were used in an “Infrastructure as a Service” capacity to provide regional weather simulations with costs ranging from $40–75 per 48-hour forecast, depending upon the configuration. Weather Research and Forecasting (WRF) model simulations provided a reasonable depiction of sensible weather elements and precipitation when compared against typical validation data available over Central America and the Caribbean. This technology has also been used by the SERVIR project and routinely produced weather forecasts to the developing countries.

With the GOES-R launch approaching, SPoRT is getting ready to use the total lightning observations from the Geostationary Lightning Mapper (GLM). A paper by George Stano et al. (2014) developed a pseudo-GLM product to help identifying “lightning jumps” associated with the onset of severe hail or tornados. This paper has been published in the Journal for Operational Meteorology.

**Supporting advances in modeling** needed for forecast improvements is evidenced through the research performed at the NASA-NOAA-DOD Joint Center for Satellite Data Assimilation (JCSDA) and NASA’s Global Modeling and Analysis Office (GMAO). Per the JCSDA partners’ request, the GMAO at Goddard Space Flight Center produced and released a global high-resolution nature run (7km-G5NR) designed for Observation System Simulation Experiments (OSSE) to be used by the partners especially by NOAA NESDIS and NWS.

The 7km-G5NR is a unique national asset, in terms of its high spatial resolution over the entire globe and the density of output data streams (three-dimensional fields are archived every 30 minutes, in order to facilitate realistic simulations of the atmospheric observing system). To document the quality of the data set, a paper was reported in 2015 by Privé and Errico to provide the detailed analysis. The spectra of analysis and forecast errors are examined in great detail. A special session on OSSE primarily focused on the use of this high-resolution nature run was held at the AMS annual meeting in January 2015. This nature run promises to have significantly wider application as well once model fields are released to the wider community.

**Understanding convection, convective processes and weather extremes** continues to focus on NASA’s precipitation missions although field programs and the Hurricane and Severe Storm Sentinel (HS3) Mission, a five-year Earth Venture Class Suborbital mission that was awarded in 2010 continues to provide invaluable data to address both inner-core and near-storm environmental science objectives to investigate hurricane intensification processes.

The **Tropical Rainfall Measuring Mission (TRMM)** was a very successful mission that allowed scientists to obtain a better understanding of weather and precipitation patterns as well as monitor hurricanes in near real time from its almost ideal 35° inclined orbit. TRMM re-entered Earth’s atmosphere in June 2015, ending over 17.5 years of data gathering. TRMM’s long-term precipitation data sets are vital for improving climate and weather forecasting models and have been used to detect hurricanes, tornado-producing convection, and extremes in precipitation patterns.

In this performance year, we focused on making progress in characterizing extreme weather events leveraging TRMM’s 17+ year record for disaster applications and improving the capability to better understand the behavior of global convective events. A study by Zhou et al. (2015) developed a prototype online extreme-precipitation monitoring system using data from the TRMM Multi-satellite Precipitation Analysis (TMPA) near-real-time precipitation product. The system utilizes estimated average recurrence intervals (ARIs) for up-to-date precipitation accumulations from the past 1, 2, 3, 5, 7, and 10 days to locate locally severe events. Initial evaluation shows that the system captures historic extreme precipitation events quite well. The system provides additional rarity information for ongoing precipitation events based on local climatology that could be used by the general public and decision makers for various hazard management applications.

Zhang et al (2015) used TMPA data in the re-forecasting of the July 2012 Beijing, China, extreme rainfall event and associated flooding that caused 79 fatalities and economic losses of $1.6 billion. Using rain gauge networks as a benchmark, this study investigated the detectability and predictability of the 2012 Beijing event via the Global Hydrological Prediction System (GHPS) forced by the NASA near-real-time TMPA and by the deterministic and ensemble precipitation forecast products from the NOAA Global Forecast System (GFS) at several lead times. The results indicated that, while somewhat variable from run to run, the disastrous flooding event was detectable by the satellite-based global precipitation observing system and predictable by the GHPS forced by the GFS 4 days in advance. TMPA has also been used to characterize the distribution and frequency of landslide events worldwide (Kirschbaum et al. 2015). Through the analysis of extreme precipitation and a Global Landslide Catalog, this study characterized the co-occurrence of extreme rainfall and rainfall-triggered landslide reports in several key hotspot landslide areas. Results suggested that TMPA rainfall can be a good predictor of increased landslide activity when evaluated against a long precipitation archive.

TRMM data has also been used to characterize extreme convection, particularly in ungauged or data sparse regions. Zuluaga and Houze (2015) documented the preferred location and diurnal cycle of extreme convective storms that occur in the tropical band containing the east Pacific Ocean, Central and South America, the Atlantic Ocean, and Northern Africa. The TRMM Precipitation Radar was used to classify the behavior of three types of convective-stratiform structures that constitute extreme convective events: deep convective cores, wide convective cores, and broad stratiform regions. These three types of events correspond to the early, middle, and late stages of convective system development and their statistics and timing of their occurrence provide insights into the life cycle and behavior of extreme precipitation within different environments. Another study by Hamada et al. (2015) evaluated PR data to establish a relationship between extreme rainfall and convective events. In this study, the authors challenge the common thought that the heaviest rainfall is linked to the tallest, most intense storms by considering 11 years of TRMM PR data in the tropics and subtropics. Their findings suggest that there is actually a relatively small fraction of extreme convective events that produce extreme rainfall rates, and rather that the most extreme rainfall is found in less intense convection settings. These findings highlight the unique capability of the 3-dimensional PR to capture the structure and height of convective events throughout the tropics and subtropics.

Drawing on the wealth of studies that use TRMM PR, a survey paper by Houze et al. (2015) reviewed and synthesized findings from different research to present a global picture of the variation of convection throughout low latitudes. The TRMM PR multi-year dataset shows convection varying not only in amount but also in its very nature across the oceans, continents, islands, and mountain ranges of the Tropics and subtropics. Shallow isolated raining clouds are overwhelmingly an oceanic phenomenon. Extremely deep and intense convective elements occur almost exclusively over land. Upscale growth of convection into mesoscale systems takes a variety of forms. Oceanic cloud systems generally have less intense embedded convection but can form very wide stratiform regions. Continental mesoscale systems often have more intense embedded convection. Some of the most intense convective cells and mesoscale systems occur near the great mountain ranges of low latitudes.

Following up on TRMM’s many years of success, the joint NASA – Japan Aerospace Exploration Agency (JAXA) **Global Precipitation Measurement (GPM)** mission is setting a new standard for precipitation measurements from space. The GPM Core Observatory, which launched Feb 28, 2014, builds off of the highly successful capabilities of TRMM and provides the most advanced precipitation measurement instruments in space. These enhanced capabilities for GPM allow improved observations of all types of precipitation, most notably light rain and snowfall. Light rain and falling snow account for about half of the precipitation in temperate mid-latitudes and cold high latitudes and are major contributors to freshwater resources in places like the United Kingdom, northern Europe, the southern Appalachian Mountains, and the snow packs of the Rocky Mountains and the Sierra Nevada.

Since data production began in March, 2014 GPM has already enabled a diverse range of applications across agencies, research institutions and the global community. Data is provided in a variety of formats that facilitate critical societal benefits in areas such as tropical cyclones, extreme weather, floods, landslides, land surface modeling, soil moisture, agriculture, fresh water availability, world health, and climate prediction.

In this early period of the GPM mission, the focus has been on data production and algorithm improvement for both instruments onboard the GPM Core Observatory as well as implementation of the Integrated Multi-satellitE Retrievals for GPM (IMERG) Level 3 algorithm. An early evaluation of the GPM Dual-frequency Precipitation Radar (DPR) has been performed to quantify the sensitivity the Ku and Ka-bands, with a focus on the Ka-band detectability of light rain and snow in comparison with the Ku-band capability (Koichi et al. 2015). The study uses storm top height (STH) as a metric of radar sensitivity. The GPM DPR Level 2 version 3 standard product is used in the analysis for the period from April to August 2014. The Ka high sensitivity (HS) mode and Ku have little systematic difference in STH over a broad range of the histogram, implying that the advantage of the Ka HS mode may not be as distinct as expected. The non-Rayleigh scattering effect may have partly offset the sensitivity advantage of the Ka HS over the Ku.

An early assessment of the GPM Microwave Imager (GMI) performance finds that the instrument has exhibited highly stable operations through the duration of the calibration/validation period following launch (Draper et al. 2015). The study provides an overview of the GMI instrument and a report of early on-orbit commissioning activities, outlining the on-orbit radiometric sensitivity, absolute calibration accuracy, and stability for each radiometric channel. Recently, GMI was determined to be the best calibrated precipitation radiometer in space.

**NASA’s efforts to develop technology needed to improve weather forecasts** was focused on two NASA Polar Winds Airborne Campaigns that were performed in this year to test the NASA developed wind lidar instruments and to support the European Space Agency (ESA) Atmospheric Dynamics Atmospheric Dynamics Mission Aeolus satellite (ADM-Aeolus) to be launched in March of 2016. ADM-Aeolus will be the first earth-orbiting wind-profiling lidar and the global wind measurements are likely to greatly improve Numerical Weather Prediction and severe weather warnings.

The first goal of the NASA Polar Winds Greenland (PWG) airborne campaign in Oct-Nov 2014 and the NASA Polar Winds Iceland (PWI) airborne campaign in May 2015 was to prepare for and demonstrate the ability to assist ESA with calibration/validation of ADM-Aeolus after its launch. The second goal was to validate numerical model representations of flows over the Greenland ice cap as well as in the offshore ice/water areas around Greenland and Iceland.

Two NASA developed lidar systems were used in these campaigns. PWG comprised the Doppler Aerosol WiNd (DAWN) horizontal wind-profiling lidar system PWI the DAWN wind lidar, the Tropospheric Wind Lidar Technology Experiment (TWiLiTE) wind lidar, and 100 dropsondes on the DC-8 aircraft. The analysis of data acquired from these campaigns will be used by ESA to both optimize the launch configuration of ADM-AEOLUS and to optimize their processing of the space-based wind measurements. A major portion of NASA’s flight hours in both campaigns was dedicated to a second science goal of demonstrating the potential of wind-profiling lidars to contribute to polar warming and ice loss science. Both airborne campaigns were successful and all of NASA’s goals were met; especially the collaboration with ESA, the mapping of barrier winds, flow splitting around Iceland, tip jet dynamics and dimensions, katabatic flow interaction with synoptic circulations and marginal ice zone roll clouds.

In this performance period, we also started planning for the future research activities. Although precipitation science continues to be a main research thrust in Weather Focus Area (WFA), we started to plan for the WFA research in the future. In December 2014, NASA issued a **ROSES element on severe storm research** to seek insights into severe storm initiation, morphology and dynamics. This program element seeks investigations that use measurements acquired from the vantage point of space to conduct basic research on the formation and intensification of severe storms that lead to the formation of tornados; and assess if satellite-based products, coupled with advanced algorithms and models, can result in more accurate forecasts and warnings. This effort is appropriately timed to contribute to ongoing efforts such as NOAA’s forthcoming Vortex-Southeast campaign.

Finally, NASA held a **Weather Focus Area Workshop** to plan for future research and development activities. With new NASA satellite, airborne, instruments, computing, and computational modeling capabilities, as well as scientific progress made in the past decade and the current budget landscape in mind, a community workshop was held on 7-9 April 2015 at Crystal City, Virginia to produce a workshop report to serve as part of the advanced planning process for the NASA Weather Focus Area. The workshop report is released through the Weather Focus Area web site (http://science.nasa.gov/media/medialibrary/2015/08/03/Weather\_Focus\_Area\_Workshop\_Report\_2015.pdf). The report identified new or enhanced research and development areas including the need for 3-D wind measurements, high spatial and temporal temperature and humidity measurements, and geostationary cloud and precipitation measurement for sever storm monitoring and forecast. Finally the workshop identified opportunities for NASA and other partner agencies jointly develop high-resolution modeling and data assimilations capabilities especially applying the capability on Observation System Simulation Experiments.

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| FY 2015 Annual Performance Indicator | FY 12 | FY13 | FY14 | FY15 |
| **ES-15-3:** Demonstrate planned progress in improving the capability to predict weather and extreme weather events. Progress relative to the objectives in NASA's 2014 Science Plan will be evaluated by external expert review. | Green | Green | Green | Green |

**Annual Performance Indicator ES-15-7: Demonstrate planned progress in enabling better assessment and management of water quality and quantity to accurately predict how the global water cycle evolves in response to climate change.**

NASA’s Water and Energy cycle focus area continues to improve understanding of the water cycle and develop tools that have led to better assessment of water quantity and will lead to improved assessment of water quality. This year, the first two global assessments ever fully informed by observations were published. The Rodell et al.(2015) study quantifies water cycle fluxes and storages during the 2000s while a companion study by L’Ecuyer(2015) et al. focuses on the energy cycle. As the two cycles are linked, each study offers insight into assessment of water quantity. Utilizing observations from several NASA satellite datasets and a framework that incorporates uncertainties, Rodell et al. close the annual water budget with less than 10% observed residuals in the majority of cases. Uncertainties in monthly budgets remain higher, often nearing or exceeding 20%. The study by L’Ecuyer et al. similarly balances the energy budget, yielding an implied residual heat flux into the oceans consistent with recent observations of changes in ocean heat content. These studies have enabled progress by others by producing water and energy cycle budget information at large basin and monthly time scales. For example, The Goddard Modeling and Assimilation Office (GMAO) are using these to validate their seven-kilometer GEOS-5 nature run and MERRA-2. Stephens and L’Ecuyer have used the data to investigate the Earth’s Energy budget that describes the energy transport across the equator and its role in the climate system (see Atmospheric Research, 2015, in press).

The Land Data Assimilation System (LDAS) and Land Information System (LIS) are NASA projects designed to assess and enable analysis of the global water cycle and develop tools that are made available to researchers and other users. In the past year, the LIS has been upgraded to assimilate remotely-sensed soil moisture from SMAP and terrestrial water storage from GRACE. It also includes a new pre-processor to generate improved model forcing with increased spatial resolution, to expand the NLDAS domain to all of North America, and to reduce the near real-time data lag from over three days to near zero. Tutorials on the software were held between NASA and NOAA/NCEP to transition the software into NCEP operations. A National Climate Assessment version of LDAS (NCA-LDAS) has also been created as an end-to-end enabling tool for sustained evaluation and dissemination of terrestrial hydrologic variables. Recent progress includes new assimilation capability of multivariate satellite data and product generation to support water indicators focused on trends during the satellite era (1979-present). These improved tools have revealed the value of different satellite systems (e.g. GRACE) to improve model estimates as well as the limitations of existing satellite products (e.g. snow water equivalent from AMSR-E) that may degrade model performance.

The January launch of the Soil Moisture Active Passive (SMAP) satellite represents the single biggest investment from the Earth Science Division on behalf of the focus area. It is the result of years of work by the focus area and all parts of the Division. The global data available from the satellite provide high resolution, high accuracy observations of soil moisture, which is at the center of the land component of the water cycle. Soil moisture influences run-off and evaporation, and serves as a nexus between the water, energy, and carbon cycles. As with most NASA satellites, SMAP will reveal aspects of the Earth system in previously unobserved parts of the world. Early data demonstrate that SMAP is able to capture global soil moisture variations and the spatial gradient of the spring landscape’s thaw.

There have been multiple studies this past year that offer new insights into the surface water aspect of the water cycle. These offer an emerging perspective on the global water cycle; previously, global climate models underrepresented the storage of water in lakes and wetlands as well as the transport mechanism of water between these and ultimately the oceans. To identify important reservoirs and fluxes of water, NASA seeks to better assess and model the physical environment that influences these water cycle components. One such example is the work of Allen and Pavelsky (2015) who have created a river width database of North America containing over 240,000 km of rivers wider than 30m. Their research shows that previous studies underestimate the number and size of rivers on the continent, enabling improved hydrological modeling and estimates of river discharge. The study argues that North American river surface area is underestimated by 20%, which could greatly affect estimates of carbon fluxes from rivers to the atmosphere. Looking forward, this team is working on a global river width database that should be available next year. The Surface Water Ocean Topography (SWOT) algorithm developers will use this global dataset. Also, Lee et al (2015) developed a method to estimate water depth in flooded forests for the first time and applied it to the Congo Basin. This novel use of multiple sources of remote sensing (PALSAR ScanSAR backscattering coefficients, Envisat altimetry, and a MODIS Vegetation Continuous Field product) offers a new method to calibrate and validate multiple aspects of 2-D hydrodynamic modeling. The study’s approach can be applied to other regions and should serve as a useful pre-launch virtual mission study for SWOT.

Looking forward to the SWOT mission, work has gone on to brief the community and help them plan to use future remote sensing assets. Three such studies came out about the expected contributions of the SWOT mission. Pavelsky et al. (2014) explores SWOT’s potential for improving space-based estimates of river discharge. They find that within the US, SWOT would match USGS river basin coverage only at large scales (> 25,000 km2). Globally, if SWOT is only able to resolve rivers wider than 100m, SWOT would substantially improve upon the Global Runoff Data Centre (GRDC) by allowing estimation of more than 60% of the river basins >50,000km2. If, however, SWOT achieves resolution of 50m rivers then the same percentage would be extended down to basins >10,000 km2. Both are drastic improvements over GRDC’s observations: <30% and <15% for the larger and smaller basins, respectively. The SWOT project and science definition team have extended this work by examining the feasibility of estimating river discharge over large areas, using a data assimilation algorithm tailored to the novel SWOT observations of water height and slope. Overall, the assimilation improved the water height estimation errors by 76%, and the discharge estimation errors by 49%. Finally, the sensitivity of the discharge estimation to errors in the SWOT observations was evaluated over the study area with those errors being described as functions of river channel characteristics, flow regime, and precipitation (i.e. wet troposphere errors). A third study, Andreadis and Schumann (2014), evaluated the potential value of using satellite observations for initializing large-scale hydraulic models for flood forecasting. They found that forecast skill was improved for water heights (with error reductions ranging from 0.2 to 0.6m/km) for lead times up to 11 days. Water height observations improved discharge forecast skill, up to 60 m3/s/km, for short forecasts (1-3 days) but had negative impacts at longer lead times.

Famiglietti (Nature, 2014) demonstrates the value of the GRACE satellites to see changes in the total water storage and trends in groundwater storage. This paper builds on and collects from studies that use GRACE and other satellite assets, both NASA and non-NASA, to determine areas of the globe undergoing anomalously high losses in groundwater. As an example, the Sacramento and San Joaquin river basins have lost roughly 15 km3 of total water annually since 2011, over half of which is estimated to be due to groundwater pumping. Similarly high groundwater pumping rates, far greater than rates of natural replenishment, were found in aquifers of the High Plains (USA), Guarani (South America), Canning (Australia), northwestern Indian and the Middle East. Additional studies by Moore et al. (2014) and Mulder et al. (2015) focus on parts of Africa and Northern Iran, respectively, and provide alternate mechanisms for water depletion such as natural depletion of groundwater and removal of water directly from lakes for irrigation. Two studies by Richey et al., (2015a, 2015b) have used GRACE to further refine groundwater loss by 1) considering different types of stress on the system and 2) by estimating timescales to groundwater depletion and the uncertainty in those estimates. As an example, they demonstrated that a groundwater depletion rate in the Northwest Sahara Aquifer System of 2.69 ± 0.08 km3/yr would result in the aquifer being depleted to 90% of its total storage in as few as 50 years givens an initial storage estimate of 70 km3.

In assessing the global water cycle, snow continues to be an important area of study without a dedicated satellite. The Airborne Snow Observatory (ASO) has continued operations and has added new watersheds (i.e. Lake’s Basin, King’s Basin, and Rush Creek) to its observed areas. Preliminary results for the Toulumne River Basin demonstrate a capability to assess snow water content and inform melt rate modeling sufficient to provide strong (R2>95%) correlations between predicted runoff and observations. Water managers who learn about and use ASO data continue to be sufficiently impressed to warrant direction of their own funds to adapt and/or plan for using this technology and approach in the future. Looking forward, ASO was added to the suite of instruments to be used in GPM’s upcoming “Olympex” validation campaign. In the fall, the ASO flew a snow-free lidar flight. A snow flight was originally scheduled for the region, but ultimately cancelled when not enough snow fell! The snow-free lidar observations may contain enough ground and vegetation information to be useful, however, to current efforts to fight and manage wildfires in the anomalously dry Olympics region.

Towards developing a future snow satellite mission, NASA has begun discussions with the community on a future field campaign, during which different observing approaches could be evaluated. The International Snow Working Group on Remote Sensing (iSWGR) has led NASA-supported meetings such as the MicroSnow2 and SnowEx workshops held in July 2015. to assemble the community to discuss issues and topics related to the development of future satellite systems, both those potentially led by NASA or other space agencies. These results would then inform discussions to determine which airborne approaches might be viable from a satellite platform. The group has also led “snow schools” to build capability in the community’s early career scientists on topics such as snow field measurement techniques and snow modeling. To improve observations during future field campaigns, NASA has invested in a potential technology to monitor the snow pack for extended periods. Roger De Roo and his team have designed, built, and tested approximately thirty wireless sensors, roughly 10x8x10cm, that can be buried in the snowpack. These devices will report local parameters such as snow density, wetness, grain size and temperature. All of these are necessary variables for future snow field campaigns designed to test airborne and satellite sensors and their snow retrieval algorithms. Special attention has been given to design the sensors so that they do not influence the snowpack environment in which they are buried.

The focus area has also supported the ongoing development of the Arctic Boreal Vulnerability Experiment (ABoVE), primarily lead by the Carbon Cycle and Ecosystems Focus area. Numerous Water and Energy cycle experts have been providing advice on relevant hydrological aspects of the ABoVE region, in particular knowledge and data related to snow and soil/freeze thaw state, and their role in seasonal vegetation activity. The P-band radar, originally developed for AirMOSS, has been used to develop and refine algorithms that to determine the depth of the Permafrost layer.

Efforts continue to address challenges in utilizing currently acquired remote sensing data in coastal and inland waters areas. Addressing such challenges, Le et al. (2014) developed a 15-year (1998-2013) time-series of satellite-derived chlorophyll-a on the Louisiana shelf, after an innovative hybrid approach to refine algorithms for both SeaWiFS and MODIS to study the relationship between surface ocean chlorophyll-a and the occurrence of deadzone. Such derived chlorophyll-a explained 70% and 50% of the interannual variability of the deadzone size for the inner shelf (depth < 10 m) and middle shelf (10 - 50 m), respectively. Mouw et al. (2015) described the current and desired state of the science and identified unresolved issues for coastal and inland waters in four fundamental elements of aquatic satellite remote sensing: mission capability, *in situ* observations, algorithm development, and operational capacity.

Individual researchers are pursuing some of these recommendations with fieldwork. One such investigation leveraged the 2014 HyspIRI/AVIRIS campaign with the flight of the Research Scanning Polarimeter (RSP) to acquire the additional data necessary for atmospheric characterization. The hyperspectral and multiangle polarimetric data collected provide a rich testbed for developing new atmospheric correction algorithms for the next-generation ocean color satellite mission. Analyses of these flights yielded 12 data sets for cloud and calibration studies, two data sets for aerosol model studies (i.e. smoke and non-spherical dust particles), and two for atmospheric correction studies. Other on-going fieldwork will assess and improve algorithm performance with airborne observations in the coastal regions around Puerto Rico, the California coast, and Lake Erie.

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| FY 2015 Annual Performance Indicator | FY 12 | FY13 | FY14 | FY15 |
| ES-15-7: Demonstrate planned progress in enabling better assessment and management of water quality and quantity to accurately predict how the global water cycle evolves in response to climate change. Progress relative to the objectives in NASA's 2014 Science Plan will be evaluated by external expert review. | Green | Green | Green | Green |