EARTH SCIENCE DIVISION

***<u>NASA Strategic Objective:</u>* Advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet.**

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<u>Annual Performance Indicator ES-14-1:</u> 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.

In the past year, NASA researchers and partners completed a series of field studies aimed at providing an unprecedented view of air pollution. DISCOVER-AQ, a NASA Earth Venture mission, is targeting the information needed to improve the ability to use satellite observations to diagnose near-surface air quality. The name is an acronym articulating the project's strategy of Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality. Satellites observing atmospheric pollutants generally provide "column" amounts, meaning that they can diagnose the total abundance of a constituent from the surface to the top of the atmosphere. By contrast, regulators are interested in what resides at the surface where populations and ecosystems are exposed to poor air quality due to unhealthy levels of ozone and particulate matter. Differentiating between pollution near the surface and aloft is a particularly difficult problem for current satellites. The mission sought to relate column-integrated and vertically-resolved observations of aerosols and key trace gases such as O_3, NO_2, and CH_2O to surface conditions.

The most recent study was performed over the Denver/Northern Front Range region of Colorado during July-August 2014. Additional observations provided by interagency and other partners included those made from the NCAR C-130 research aircraft (NSF and State of Colorado), ground network augmentation of nitrogen oxide measurements and testing of small air quality sensors (EPA), tall tower observations and augmented ozone and wind lidar observations (NOAA and multiple universities), extended observations in Rocky Mountain National Park (US Forest Service), and six mobile labs (NASA, NOAA, and multiple universities).

These observations will be combined with information gathered in previous campaigns to the Baltimore-Washington area in July 2011, the southern San Joaquin Valley of California in January-February 2013, and Houston, Texas in September 2013 to better understand the factors controlling air quality and improve both remote sensing strategies and the design of ground-based networks in advance of geostationary air quality observations by TEMPO (Tropospheric Emissions: Measurements of Pollution) planned for 2019.

The NASA Airborne Tropical Tropopause Experiment (ATTREX) is a series of airborne campaigns focused on understanding physical processes in the Tropical Tropopause Layer (TTL) and their role in atmospheric chemistry and climate. The TTL is a transition layer between the troposphere and stratosphere, and air entering the stratosphere passes through this layer. Therefore, processes occurring in the TTL ultimately control the composition of the stratosphere. A particular ATTREX emphasis is to understand the dehydration of air as it passes through the cold tropical tropopause region. ATTREX is using the high-altitude, long-duration NASA Global Hawk Unmanned Air System to make in situ and remote-sensing measurements spanning the Pacific.

During January-March, 2014, the Global Hawk was deployed to Guam for ATTREX flights. Despite numerous Global Hawk operations problems, six science flights were conducted from Guam, resulting in over 100 hours of Western Pacific TTL sampling and about 180 vertical profiles through the TTL. The numerous tracers measured on the vertical profiles will provide information about TTL dynamics, transport pathways, and transport time scales. The flights included sampling both within and downstream of the Western Pacific cold pool and sampling in the outflow of numerous deep convection systems, including two mature typhoons. The final phase of ATTREX will be focused analysis of the extensive dataset and modeling to address the TTL science questions and improve representation of TTL processes in climate models.

The Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) flew its 500th science flight hour during May 2014, successfully completing its Baseline Science Investigation Requirements, quantifying correlations between atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4) with surface-atmosphere carbon fluxes and surface state control variables (soil moisture, freeze-thaw state, inundation state, surface soil temperature) and elucidating the sensitivities of Arctic carbon cycle processes to climate change.

October 2013 brought Interior Alaska +8-10°C land surface temperature anomalies, monthly rainfall approaching the annual average, and rain falling on bare ground. The persistence of late-summer conditions through the end of October is consistent with trends expected for the northern high latitudes by the mid- to late-21st century, but unprecedented in over 100 years of the instrument weather record. During flights on 25-27 October 2013, CARVE observed +10-30 ppm and +50-200 ppb enhancements in boundary layer concentrations of CO_2 and CH_4, respectively, throughout the Tanana-Kuskakwim lowlands. The estimated surface-atmosphere CO_2 and CH_4 fluxes show little change from those found in the late summer, and indicate minimal slowing in soil respiration rates despite the late date.

Studies quantifying the emissions of atmospheric trace gases and reconciling top-down and bottom-up approaches were a focus of research during this past year. The recently concluded Stratospheric-Troposphere Processes and their Role in Climate (SPARC) report on “Lifetimes of Stratospheric Ozone-Depleting Substances, Their Replacements, and Related Species” was released in March 2014. It was motivated by findings that the lifetimes of some of the ozone depleting substances (i.e., CFC-11 and CCl_4) could be longer than previously accepted and because some of the replacement compounds were not yet in use at the time of the last evaluation in the 1990s. A recently published study of the atmospheric abundance of CCl_4 (Liang et al., 2014) concluded that its near-zero 2007–2012 emissions estimate (based on the UNEP reported production and feedstock usage) cannot be reconciled with its observed slow decline of atmospheric concentrations and its inter-hemispheric gradient. At a minimum, mean global emissions of 34 Gg/yr after 2000 are required to reproduce the observed inter-hemispheric gradient.

In another study, Miyazaki and Eskes (2013) focused on estimating surface NOx emissions using a combined assimilation of satellite observations of NO_2, CO, O_3, and HNO_3 with a global chemical transport model. The assimilation of measurements for species other than NO_2 provided additional constraints on the NOx emissions by adjusting the concentrations of the species affecting the NOx chemistry and leads to changes in the regional monthly-mean emissions and the annual total emissions. Validation against independent observations and comparisons with the recent Regional Emission inventory in Asia version 2.1 emissions shows that the multiple species assimilation improved the chemical consistency, including the relation between concentrations and the estimated emissions.

The quantification of tropical emissions of methane from fires was studied using tropospheric methane and CO data from the Aura Tropospheric Emission Spectrometer (TES) and new CO profile measurements from the Terra Measurements of Pollution in the Troposphere (MOPITT) satellite instruments together with the Goddard Earth Observing System (GEOS)-Chem model to estimate methane emissions from burning in Indonesia (Worden et al., 2013). The El Niño related Indonesian fires increased the tropical distribution of atmospheric methane relative to 2005, indicating that tropical biomass burning can compensate for expected decreases in tropical wetland methane emissions from reduced rainfall during El Niño as found in previous studies.

The composition of the stratosphere and its interaction with the upper troposphere continues to attract considerable interest in the community. Neu et al. (2014) quantified variations in the stratospheric Brewer-Dobson circulation. The downward transport of stratospheric ozone is an important natural source of tropospheric ozone, particularly in the upper troposphere, where changes in ozone have their largest radiative effect. Since stratospheric circulation is projected to intensify over the coming century, this could lead to an increase in the flux of ozone from the stratosphere to the troposphere. However, large uncertainties in the stratospheric contribution to trends and variability in tropospheric ozone levels make it difficult to reliably project future changes in tropospheric ozone. Satellite measurements of stratospheric water vapor and tropospheric ozone levels collected between 2005 and 2010 were used to assess the impact of changes in stratospheric circulation, driven by El Niño/Southern Oscillation and the stratospheric Quasi-Biennial Oscillation, on tropospheric ozone levels. It was found that interannual variations in the strength of the stratospheric circulation of around 40% - comparable to the mean change in stratospheric circulation projected this century - lead to changes in tropospheric ozone levels in the northern mid-latitudes of around 2%, approximately half of the interannual variability. It is suggested that the projected intensification of the stratospheric circulation over the coming century could lead to small, but important increases in tropospheric ozone levels.

Dessler et al. (2013) showed that stratospheric water vapor variations play an important role in the evolution of our climate. This came from analysis of Aura Microwave Limb Sounder (MLS) observations that showed that stratospheric water vapor increased with tropospheric temperature, implying the existence of a stratospheric water vapor feedback. The authors estimated the strength of this feedback in a chemistry–climate model would be a significant contributor to the overall climate sensitivity. One-third of this feedback comes from increases in water vapor entering the stratosphere through the tropical tropopause layer, with the rest coming from increases in water vapor entering through the extratropical tropopause.

A separate study (Santee et al., 2013) demonstrated the importance of methyl chloride in upper tropospheric/lower stratospheric (UTLS) processes. CH_3Cl is by far the largest natural carrier of chlorine to the stratosphere. Its importance in stratospheric ozone chemistry is expected to increase in the coming decades as emission controls alter the relative contributions from natural and anthropogenic halogen sources. MLS measurements provided the first daily global observations of CH_3Cl. The researchers exploited the 8-year MLS data set to investigate the spatial, seasonal, and interannual variations in the distribution of CH_3Cl in the UTLS. Like carbon monoxide, CH_3Cl is a marker of pollution from biomass burning that can be lofted to the UTLS very rapidly by deep convection. Methyl chloride is shown to be very useful as a tracer of large-scale dynamical processes, such as diabatic descent inside the stratospheric winter polar vortices, quasi-isentropic cross-tropopause transport associated with the summer monsoon circulations, and effects related to the quasi-biennial oscillation and the tropical “tape recorder”.

The impacts of Asian pollution and its inter-hemispheric transport were investigated by multiple researchers. Strode and Pawson (2013) looked at the detection of trends in carbon monoxide (CO) from Asian emissions in the presence of its large interannual variation from biomass burning. Using the MOPITT instrument and a multiyear model, they found the 3% yr^{-1} trend in Asian anthropogenic emissions predicted by the model would lead to a statistically significant trend in CO surface concentration in the western United States within 12 years, and accounting for Siberian boreal biomass-burning emissions greatly reduces the record length needed for trend detection. Combining the modeled trend with the observed MOPITT variability at 500 hPa, they estimated that the 3% yr^{-1} trend could be detectable in satellite observations over Asia in approximately a decade. Their predicted timescales for trend detection highlight the importance of long-term measurements of CO from satellites.

The value of using multiple space-based data sets in elucidating atmospheric processes was demonstrated by many researchers this past year. For example, Li et al. (2014) used satellite-derived global aerosol properties from multiple instruments to constrain climate model aerosol parameterizations. Using a combined principal component analysis approach, a comparison was performed of monthly mean, mapped aerosol optical depth (AOD) product from Moderate Resolution Imaging Spectroradiometer (MODIS), Multiangle Imaging Spectroradiometer (MISR), and Ozone Monitoring Instrument (OMI). The results suggested that all of the sensors captured the globally important aerosol regimes, including dust, biomass burning, pollution, and mixed aerosol types, albeit with some differences. These differences, e.g., that MISR AOD data exhibited overall lower variability in South America and the Sahel compared with MODIS, were characterized in detail to better understand the strengths and weaknesses of the various satellite sensors.

Thirty years since the discovery of the Antarctic ozone hole and twenty-seven years after the signing of the Montreal Protocol on Substances that Deplete the Ozone Layer, a review of the scientific understanding of the ozone hole and our understanding of the polar atmosphere was published. It was noted that the worldwide response to the discovery was fast, but the recovery in ozone is slow. Ground and satellite observations show that chlorine levels in the troposphere and stratosphere are decreasing and model projections suggest that ozone will return to 1980 levels between 2050 and 2070. The authors conclude that the disappearance of the ozone hole will symbolize the possibility of protecting Earth through cooperative actions (Douglass et al., 2014).

FY2014 Annual Performance Indicator	FY 11	FY12	FY13	FY14
ES-14-1: 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

<u>Annual Performance Indicator ES-14-3:</u> Demonstrate planned progress in improving the capability to predict weather and extreme weather events.

During fiscal year 2014 NASA sponsored research continued to provide new insights into weather and extreme-weather events, based on data obtained from a variety of satellite platforms (GOES, Tropical Rainfall Measuring Mission (TRMM), Aqua, Terra, Suomi-NPP, CloudSat, and CALIPSO) and a field experiment. A core component of this theme is the support for the precipitation missions (TRMM and GPM) and the process studies that relate directly to weather and weather extremes in addition to climate.

After nearly 17 years in space, TRMM's fuel finally ran out during summer 2014 but the satellite will continue to operate into 2016 as it slowly descends toward the Earth's surface. TRMM's long-term precipitation data sets are vital for improving weather forecasting models and being able to detect hurricanes, tornados and extremes in precipitation patterns (Hou et al., 2014). In 2014, NASA scientists developed a prototype online extreme precipitation monitoring system from 15-years of TRMM Multi-satellite Precipitation Analysis (TMPA) data, demonstrated strong relationship between changes in global rainfall pattern and the Hadley circulation (Lau et al., 2014), characterized the precipitation features and annual rainfall patterns during the TRMM era in the Central Andes (Mohr et al., 2014), and updated the oceanic precipitation rate and its zonal distribution (Zhou et al, 2014).

In addition, an updated 15-yr TRMM composite climatology (TCC) was presented and evaluated in an article in the Journal of Climate (Wang, J.J. et al, 2014). This climatology is based on a combination of individual rainfall estimates made with data from the primary TRMM instruments: the TRMM Microwave Imager (TMI) and the precipitation radar (PR). This combination climatology of passive microwave retrievals, radar-based retrievals, and an algorithm using both instruments simultaneously provides a TRMM-based best estimate of the mean precipitation over the tropics. The dispersion of the three estimates, as measured by the standard deviation among the estimates, is presented as a measure of confidence in the final estimate and as an estimate of the uncertainty thereof. In general, the TCC values confirm ocean estimates from the Global Precipitation Climatology Project (GPCP) analysis, which is based on passive microwave results adjusted for sampling by infrared-based estimates. Comparison of the TCC values (and the input products) to gauge analyses over land indicates a small bias of the radar-based estimates and relatively large biases of the passive microwave algorithm. Comparison with surface gauge information from western Pacific Ocean atolls shows a negative bias for all the TRMM products. However, the representativeness of the very limited number of atoll gauges of open-ocean rainfall is questioned in this paper.

February 2014 saw the launch of NASA's Global Precipitation Measurement (GPM) Mission core satellite. The GPM Mission Integrated Precipitation and Hydrology Experiment (IPHEx) took place in the Appalachian Mountains of southwestern North Carolina from May 1 – June 15, 2014. GPM IPHEx partners included Duke University and the NOAA Hydrometeorological Testbed. Overarching campaign objectives included the improvement of satellite-based remote sensing algorithms of clouds and precipitation over mountainous terrain, and evaluation and further development of associated data products for use in hydrologic applications such as flood prediction. To achieve these objectives an extensive set of airborne and ground-based instruments were deployed and operated under occasional overpasses of GPM constellation satellite platforms. Participating aircraft included the NASA ER-2 and University of North Dakota Cessna Citation. At high altitude, the ER-2 served as a "proxy" satellite platform carrying the AMPR and CoSMIR radiometers spanning frequencies from 10-183 GHz, and the CRS, HIWRAP, and NEXRAD radars covering the W, Ka, Ku, and X bands. Indeed, IPHEx was the first NASA field effort to ever deploy and operate four cloud and precipitation radar frequencies from the same high-altitude airplane. The University of North Dakota Cessna Citation aircraft carried a suite of in situ cloud microphysics probes to sample cloud and precipitation processes within the field of view of ER-2 and ground-based instruments. At the ground, an extensive array of NASA and NOAA multi-parameter radars (NASA NPOL and D3R radars, NOAA NOXP radar), disdrometers, rain and stream gauge networks were deployed and operated on a 24/7 basis to complete observations of precipitation formation and movement through the coupled atmosphere-hydrologic system. IPHEx scientists successfully collected 113 hours of ER-2 and 78 hours of Citation airborne data and six full weeks of ground-based science data over a wide variety of storm types ranging from heavy raining mountain cloud systems that produced strong hydrologic response, severe hail storms, to smaller and more lightly raining maritime clouds. Collectively the IPHEx observations will provide a comprehensive view of orographic precipitation processes, the manifestation of those processes in GPM spaceborne measurements, and subsequently how to better estimate precipitation rates over complex terrain.

A process study (Kidd, Chris et al., *Journal of Hydrometeorology*, 2014) compared the precipitation derived from the ECMWF operational forecast model with satellite precipitation datasets to assess the mean annual and seasonal diurnal rainfall cycles. The analysis encompassed the global tropics and subtropics (40 degrees N-40 degrees S) over a 7-yr period from 2004 to 2011. It was found that during the first half of the analysis period the ECMWF model overestimated precipitation by up to 15% in the tropics, although after the implementation of a new convective parameterization in November 2007 this bias fell to about 4%. The ECMWF model poorly represented the diurnal cycle, simulating rainfall too early compared to the TMPA and TRMM PR products; the model simulation of precipitation was particularly poor over Indonesia. In addition, the model did not appear to simulate mountain-slope breezes well or adequately capture many of the characteristics of mesoscale convective systems. The work highlights areas for further study to improve the representation of subgrid-scale processes in parameterization schemes and improvements in model resolution. According to Kidd et al. 2014, the proper representation of sub-daily precipitation in models is critical for hydrological modeling and flow forecasting.

A modeling study developed a coupled land surface and routing model and real-time global flood estimation tool using TRMM TMPA precipitation data (Wu, Huan et al., Water Resources Research, 2014). A widely used land surface model, the Variable Infiltration Capacity (VIC) model, was coupled with a newly developed hierarchical dominant river tracing-based runoff-routing model to form the Dominant river tracing-Routing Integrated with VIC Environment (DRIVE) model. DRIVE serves as the new core of the real-time Global Flood Monitoring System (GFMS). The GFMS uses real-time satellite-based precipitation to derive flood-monitoring parameters for the latitude band 50 degrees N-50 degrees S at relatively high spatial (approximate to 12 km) and temporal (3 hourly) resolution. Examples of model results for recent flood events are computed using the real-time GFMS. To evaluate the accuracy of the new GFMS, the DRIVE model is run retrospectively for 15 years using both research-quality and real-time satellite precipitation products and the results show the research-quality precipitation input produce only slightly better flood occurrence, flood evolution, and magnitude, indicating TRMM TMPA data may be used operationally for flood-monitoring and forecast purposes.

While advances in the utilization of TRMM data continue, NASA launched the Global Precipitation Measurement (GPM) mission, an international satellite mission specifically designed to set a new standard for the measurement of precipitation from space and to provide a new generation of global rainfall and snowfall observations in all parts of the world every 3 hours. The National Aeronautics and Space Administration (NASA) and the Japan Aerospace and Exploration Agency (JAXA) successfully launched the Core Observatory satellite on 28 February 2014 carrying advanced radar and radiometer systems to serve as a precipitation physics observatory. This will serve as a transfer standard for improving the accuracy and consistency of precipitation measurements from a constellation of research and operational satellites provided by a consortium of international partners. GPM will provide key measurements for understanding the global water and energy cycle in a changing climate as well as timely information useful for a range of regional and global societal applications such as numerical weather prediction, natural hazard monitoring, freshwater resource management, and crop forecasting.

In preparation for the availability of GPM data, many of the funded research and developments in the weather focus area have been to develop the GPM data processing and distribution pipeline and to prepare for the GPM data assimilation into global weather prediction systems. Scientists at the Global Modeling and Assimilation Office at NASA Goddard Space Flight Center are working to assimilate GPM Microwave Imager (GMI) radiance measurements using a recently developed all-sky (clear, cloudy, and precipitating) data assimilation methodology to utilize GPM Microwave Imager (GMI) radiance data in GEOS-5 global model to improve global cloud and precipitation analyses. This will ultimately improve near-real time weather forecasts including severe storms and hurricanes as well as improve global cloud and precipitation analyses. Previous uses of microwave imager data either neglected measurements affected by clouds and precipitation in radiance space or assimilated retrieved rain rates using highly inflated error estimates to limit their impact.

Current efforts have considered first the sensitivity of the system to clear-sky measurements from TMI and GMI (Jin et al. 2014). This effort has shown that these observations have a net drying effect, which is resulting from a skewed distribution of of the difference between the observations and forecasted observation based on the modeled atmospheric state, or "observation departures". The result has led to a reevaluation of quality control (QC) procedures that have been extended from heritage microwave imagery, namely SSM/I. In addition, the work being done to extend to all-sky conditions is hoped to normalize the distribution away from the dry-bias.

The all-sky microwave assimilation methodology has been implemented and extended to use GMI radiances, and initial results focusing on Hurricane Arthur have shown that the observations are in fact adjusting the cloud analysis (Kim et al. 2014). In addition to adjusting the prognostic model cloud fields, the underlying dynamic and thermodynamic fields must also be adjusted so that the clouds don't simply fall or evaporate upon insertion into the model. To accomplish this, the GEOS-5 cloud physics schemes have been linearized and are incorporated into the data assimilation system, so that they are adjusted in a physically consistent manner.

With the convergence of these efforts with further advancements in data assimilation methodology, including 3D/4D Variational/Ensemble Hybrid system and advances in observation error modeling, the GMAO is on the verge of being able to routinely assimilate these observations in near-realtime. Additionally, software to preprocess and assimilate (reading and QC routines in the GSI assimilation system) have been passed to the NCEP GSI repository and utilized by NESDIS scientists under the auspices of the Joint Center for Satellite Data Assimilation (JCSDA).

The European Centre for Medium-Range Weather Forecasts (ECMWF) continues to show the extremely important impact on operational weather forecasts of assimilating

AIRS observations - second only to the collective impact of assimilating four Advanced Microwave Sounding Unit (AMSU) units. Major Numerical Weather Prediction (NWP) centers in the U.S. – NOAA/NCEP, NASA Global Modeling and Assimilation Office (GMAO), and the U.S. Navy – have also all shown notable improvements from the assimilation of AIRS data into their operational forecast systems.

GMAO has been an early adopter of new observations into the analyses. This includes data from Suomi-NPP. Infrared radiances from CrIS and microwave radiances from ATMS have been included into the GEOS-5 assimilation system. A study of observation impacts, which has been facilitated by the development of an adjoint of the complete data assimilation system, demonstrates modest benefits of including these data. This early success provides a basis for future developments in the GEOS-5 analyses, both to increase the weighting given to these new observations in the analysis system and to decrease the impacts of older data types, such as the AIRS infrared radiances from EOS-Aqua, which is now an aging platform. GMAO scientists are working to include cloud- and aerosol-contaminated satellite radiance measurements, in the infrared and microwave part of the observed spectrum, into the weather analysis system. This effort in GMAO contributes to the national capability of using many more observations in critical, cloud-affected regions in weather analysis systems. A particular emphasis of GMAO's system development is the adoption of NASA's Global Precipitation Mission (GPM) microwave radiance data from the GPM Microwave Imager (GMI). Less than six months after launch of the GPM platform, in February of 2014, the all-sky GMI radiances are being incorporated into development versions of the GEOS-5 data assimilation system. Once validated, this development will be incorporated into production versions of GEOS-5 and also exchanged with partners in the Joint Center for Satellite Data Assimilation (JCSDA). This latter step will allow adoption of these new data by NOAA/NCEP, the Navy, and other agencies.

At the Short-term Prediction Research and Transition (SPoRT) center extensive progress was made to transition new, cutting-edge satellite datasets and products from the suite of instruments on the Suomi-NPP satellite and precipitation estimates in data void regions from the Global Precipitation Mapping (GPM) mission. For example, VIIRS RGB imagery ahs been used by National Weather Service forecasters for smoke and hot spot detection, fog and cloud composition, and dust transport forecasts (Stano et al., 2014). Early GPM GMI data had been transitioned to the National Hurricane Center Proving Ground and integrated with the NAWIPS display system. Forecasters at Central Pacific Hurricane Center (CPHC) used the 89 GHz RGB product from GPM during Hurricane Iselle (August 2014). The number of operational weather entities using data from NASA research instruments has substantially grown and includes National forecast centers for hurricanes, and continental and marine weather prediction. Disaster response agencies are using SPoRT imagery and power outage products to assist in assessment and monitoring recovery from devastating tropical storms and tornadoes (Molthan et al., 2014). Efforts in using the VIIRS DNB for disaster response have been well-received by the NASA Administrator and acknowledged through both Center and Agency Group Achievement Awards.

FY 2014 Annual Performance Indicator	FY 11	FY12	FY13	FY14
ES-14-3: 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

<u>Annual Performance Indicator ES-14-6:</u> 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.

Hansen et al. (2013) in a landmark paper in *Science* used Landsat satellite data to map global forest loss and gain from 2000 to 2012 at a spatial resolution of 30 meters. Results from time-series analysis of over 650,000 Landsat images showed the tropics as the only climatic domain to exhibit a trend of increasing forest loss. Brazil's well-documented reduction in deforestation was offset by increasing forest losses in Indonesia, Malaysia, Paraguay, Bolivia, Zambia, Angola, and elsewhere. Intensive forestry and logging practiced within subtropical forests resulted in the highest rates of forest change globally. Boreal forest loss, due largely to fire and forest harvest, was second to that in the tropics in absolute and proportional terms. These results, for the first time, depict a globally consistent and locally relevant record of forest change at the landscape scale.

Discoveries made during the 2011-2012 Impacts of Climate on the EcoSystems and Chemistry of the Arctic Pacific Environment (ICESCAPE) field campaign were fully documented in a 2014 special issue of Deep-Sea Research II (Arrigo (Ed), 2014). The special issue is entitled, "The Phytoplankton Megabloom beneath Arctic Sea Ice: Results from the ICESCAPE (Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment) program." In July 2011, blooms of phytoplankton (microscopic marine plants) beneath the ice were observed to extend from the sea-ice edge to 72 miles into the ice pack. In 2012, scientists punched through three-foot thick sea ice to find waters richer in these phytoplankton than any other ocean region on Earth. The phytoplankton growth rates reported are among the highest ever measured for polar waters. Researchers have estimated that phytoplankton production under the ice in parts of the Arctic could be up to 10 times higher than in the nearby open ocean. Fast-growing phytoplankton consume large amounts of carbon dioxide. The papers in the special issue (e.g., Arrigo et al., 2014; Balch et al., 2014; Laney and Sosik, 2014; Lowry et al., 2014; Neukermans et al., 2014; Ortega-Retuerta, 2014; Spall et al., 2014) explore the potential mechanisms and causes of the bloom, and conclude that scientists will have to reassess the amount of carbon dioxide entering the Arctic Ocean through biological activity if the under-ice blooms turn out to be common. The finding reveals a new consequence of the Arctic's warming climate and provides an important clue to understanding the impacts of a changing climate and environment on the Arctic Ocean and its ecology.

Remote sensing research on global terrestrial primary productivity and phenology continues within the NASA program. Current research emphasizes the effects of environmental change on these ecosystem properties and the implications for carbon sources and sinks. Many publications in 2014 documented responses to changing temperature or hydrological regimes (Keenan et al., 2014; Yi et al., 2014; Peng et al., 2013). Some identified anomalous time periods (strong deviations from the average) and related those changes to environmental factors (Bastos et al., 2013; Friedl et al., 2014). For example, Bastos et al. (2013) attributed a high global net primary productivity (NPP) anomaly (from MODIS) for 2011 to the strong La Nina that lasted from late 2010 to early 2012. They report that El Nino/Southern Oscillation (ENSO) explains more than 40% of global NPP variability, mainly driven by the response of Southern Hemisphere ecosystems, particularly in tropical and subtropical regions.

Friedl et al. (2014) exploited two recent climate anomalies to explore how the springtime phenology of Northeastern temperate deciduous forests may respond to future climate warming. Springtime temperatures in 2010 and 2012 were the warmest on record in the Northeastern United States. They analyzed near surface air temperatures, time series of MODIS-derived vegetation indices, and *in situ* phenological observations. The observations detected that leaf emergence occurred up to two weeks earlier than normal, but with significant sensitivity to the specific timing of thermal forcing.

Keenan et al. (2014) assessed changes over the past two decades in phenology of temperate forests for the eastern U.S. and quantified the resulting changes in forest carbon storage. They analyzed satellite vegetation indices and ground observations of phenology and carbon dioxide fluxes using 18 terrestrial biosphere models. They reported strong trends of earlier spring and later autumn. They showed that carbon uptake through photosynthesis increased considerably more than carbon release through respiration for both an earlier spring and later autumn. They found that the terrestrial biosphere models tested misrepresent the temperature sensitivity of phenology, and thus the effect on carbon uptake. Their analysis of the temperature-phenology-carbon coupling suggests a current and possible future enhancement of forest carbon uptake due to changes in phenology -- a negative feedback to climate change that will serve to slow the rate of warming.

Other publications focused on changes in land use (e.g., agricultural conversion, over-grazing) and nutrients and their effects on productivity (Cleveland et al., 2013; Mueller, et al., 2014; Hilker et al., 2013; Smith et al., 2014; Turner et al., 2013). Smith et al. (2014) investigated the impact of agriculture on NPP. They demonstrated that agricultural conversion has reduced terrestrial NPP globally by 7%. Increases in NPP due to agricultural conversion were observed only in areas receiving external inputs (i.e., irrigation and/or fertilization). NPP reductions were found for 88% of agricultural lands, with the largest reductions observed in areas formerly occupied by tropical forests and savannas.

Turner et al. (2013) used models to produce estimates of net ecosystem exchange (NEE), a term that that includes emissions from decomposition/respiration of harvested forest and agricultural products, CO_2 evasion from streams and rivers, and biomass burning in its accounting of net productivity. They found that these emissions counteracted a significant proportion (35%) of the carbon taken up by North American ecosystems.

Two important 2014 publications examined species vulnerability and extinction risk due to climate change. A major review paper by Pimm et al. (2014) in *Science* links our knowledge of patterns in biogeography (spatial phenomena) to theories about extinction (demographic phenomena) in order to address issues of practical importance in conservation biology. It shows the power -- in the terrestrial realm -- of using global datasets of forest cover change derived from the 1990, 2000, and 2005 epochs of the Global Land Survey Collection of Landsat images to improve global biodiversity datasets. The importance of global satellite imagery of forest cover lies in its use in refining global range maps of species with more current land cover data so that the maps more accurately show where forest species are likely to occur. Thus, the paper demonstrates the power of combining NASA and other satellite datasets with species range information and population data to track the degree of threat to species at a global scale. The authors note that current rates of extinction are about 1000 times the likely background rate of extinction and future rates are poised to increase.

Pearson et al. (2014) developed a simulation approach based on generic life history types to show that extinction risk due to climate change can be predicted using a mixture of spatial and demographic variables that can be measured without the need for complex forecasting models. Most of the variables found to be important for predicting extinction risk, including occupied area and population size, are already used in species conservation assessments, indicating that present systems may be better able to identify species vulnerable to climate change than previously thought.

Extreme events, including unusually severe fires, tropical cyclones, flooding, and drought occurrences, have been the focus of a number of studies reported in the past year as well as a topic (i.e., extreme drought and flooding) emphasized in NASA's recent Interdisciplinary Science program selection. Research publications included work on defining and characterizing extreme fires (Birch et al. 2014, Lannom et al. 2014); correlating extreme events with observed ecosystem characteristics -- mostly indicators of vegetation productivity (John et al. 2013, Negron-Juarez et al. 2014, Zhou et al. 2014); and evaluating the impacts of these events on ecosystem functioning, e.g., net carbon balance and recovery (Fisk et al. 2013, Jones et al. 2013).

Research on the occurrence, extent, and severity of fires, including some extreme fires, yielded important findings in 2014. Chen et al. (2013) examined long-term trends and interannual variability of fires for South America during 2001–2012 using multiple satellite-derived fire products. Active fires in tropical forests increased significantly during 2001–2005, and this trend was attributed primarily to deforestation. Fires decreased slightly between 2005 and 2012, with year-to-year changes associated with climate extremes. Fires in savannas and evergreen forests increased in parallel during drought events in 2005, 2007 and 2010. Deforestation fire intensity (the number of fires per unit of deforested area) increased significantly within the Brazilian Amazon in areas with small-scale deforestation. These authors concluded that fires associated with forest degradation are becoming an increasingly important component of the fire regime and associated carbon emissions. Lin et al. (2014) investigated fires in croplands, plantations, and rangelands in the U.S. in order to assess their contributions to fire emissions relative to fires in wildlands. They quantified decadal trends of Terra MODIS observations of active fires (thermal anomalies) as a function of management type during 2001–2010. Cropland and prescribed/other fire types combined were responsible for 77% of the total active fire detections within the U.S and were most abundant in the south and southeast. Their analysis suggests it may be possible to modify landscape fire emissions within the U.S. by altering the way fires are used in managed ecosystems. A review paper (Yebra et al., 2013) assessed readiness to utilize remotely sensed live fuel moisture content (LFMC) in operational fire risk assessment. This paper identified remaining challenges in quantifying errors and linking LFMC to fire behavior and risk and recommended priority areas for work to advance this important application.

Urban ecosystems are receiving growing attention, both as settings for major land cover and land use change impacts as well as for their role in global carbon emissions. Coastal cities are also of great interest with respect to the impacts of sea level rise and extreme hydrological events. A variety of findings have been reported. A NASA Interdisciplinary Science project on mega-urban changes and impacts (Nghiem et al., 2014) reported that traditional approaches using satellite optical/spectral sensors may have underestimated the urbanization of Beijing and other megacities in China. This group has found SeaWinds scatterometer data helpful for evaluating changes in urban systems, including a recent study of groundwater vulnerability that makes use of relationships between land use changes and groundwater contamination (Stevenazzi et al., 2014). Zhou et al. (2014) mapped urban extent in the United States and China using the DMSP/OLS nighttime stable light data. Their methodology reduces over- and under-estimation issues in mapping urban extent over large areas. Frolking et al. (2013) analyzed macroscale changes in urban 3-dimensional structure from 1999 through 2009 by combining the DMSP/OLS data (for horizontal extent) with SeaWinds microwave scatterometer data (for vertical extent). They report large increases in built-up infrastructure worldwide and show that cities are expanding both outward and upward. They have detected previously undocumented recent and rapid changes in urban areas worldwide. New NASA Carbon Monitoring System and Carbon Cycle Science program research projects are investigating the carbon emissions from cities and urbanized regions in the U.S., including the Boston-D.C. corridor, urbanized California and New

Hampshire landscapes, and the Los Angeles megacity (http://carbon.nasa.gov/cgi-bin/cms/cms_projects.pl).

Coastal regions are dynamic and of great interest because of the changes they are experiencing due to human activities and climate change. The contributions of coastal margins to regional and global carbon budgets are not well understood, largely due to limited information about the magnitude, spatial distribution, and temporal variability of carbon sources and sinks in coastal waters. A 2013 paper in *Nature* (Bauer et al., 2013) discussed the sources, exchanges and fates of carbon in the coastal ocean and how anthropogenic activities have altered carbon cycling in the coastal ocean. It provides recent evidence suggesting the coastal ocean may have become a net sink for atmospheric carbon dioxide during post-industrial times. In related North American Carbon Program-sponsored (and NASA-funded) synthesis activities focused on coastal carbon, two major milestones were achieved in 2014. For the first, the final report of the U.S. Gulf of Mexico Carbon Cycle Synthesis Workshop was published (Benway and Coble (Ed), 2013). The Gulf of Mexico coastal synthesis workshop brought together scientists studying the Gulf of Mexico and is drainage sources to develop an updated carbon budget of the region. The second major milestone was the final workshop of the Coastal CARbon Synthesis (CCARS) in August 2014. This CCARS Community Workshop represented the culminating activity 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 purposes of the workshop were to: 1) present draft carbon budgets to the community for final refinement, and 2) develop a community plan for future research activities to improve understanding of carbon cycling in coastal waters. This culminating community workshop gathered together researchers to share the outcomes of the regional CCARS activities, identify major gaps in coastal ocean research and observational coverage, and develop core recommendations for a science plan 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. Accomplishments in 2014 include the publication of key papers on the U.S. biomass data product (Zhang et al., 2014), the global carbon flux product (Liu et al., 2014), and capabilities needed for a carbon monitoring system (West et al., 2013). A major report to Congress was prepared and delivered. The CMS project has developed one of the most advanced carbon data assimilation systems in the world that integrates satellite and surface observations related to anthropogenic, oceanic, terrestrial and atmospheric carbon. In the past year, new CMS studies have gotten underway utilizing commercial off-the-shelf airborne measurement methodologies in support of international Reducing Emissions from Deforestation and forest Degradation (REDD), and REDD+ projects in Indonesia, Mexico, Peru, and Brazil, as well as carbon sequestration, management, and state-level mapping projects within the U.S. The selection of new CMS investigations made in July 2014 included studies to improve the CMS biomass and flux products and to conduct new MRV-relevant projects at local to regional scales, including several state-level biomass/carbon stock mapping projects within the U.S. and projects to quantify carbon in coastal ecosystems relevant to “blue carbon” objectives of reducing carbon emissions by conserving and sustainably managing a coastal carbon sink.

Evaluation and improvement of ecosystem and biogeochemical cycling models is fundamental to the improvement of predictive capability. In the past year significant new milestones have been achieved and modeling results reported in this domain. Three major studies provide examples. The Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP), funded primarily by NASA and endorsed as a USGCRP North American Carbon Program synthesis activity, has released major simulation results (Huntzinger et al. 2014a), driver data sets (Wei et al. 2014), model structure comparisons (Huntzinger et al. 2014b), and published on its design (Huntzinger et al. 2013), driver data development (Wei et al. 2013) and analytical approaches. Scientific analyses based on MsTMIP simulations include the assessment of the impacts of large-scale temperature and precipitation extremes on biospheric carbon fluxes (Zscheischler et al., 2014) and the examination of the sensitivity of global gross primary production to hydrologic states (Lei et al. 2014), among others. MsTMIP is a formal multi-scale synthesis, with prescribed environmental and meteorological drivers shared among model teams, and simulations standardized to facilitate comparison with other model results and observations through an integrated evaluation framework. The majority of the models participating in this intercomparison rely directly on a broad range of NASA remote sensing observations, as do some of the evaluation datasets. MsTMIP provides feedback to the terrestrial biospheric modeling community with the goal of improving the diagnosis and attribution of carbon sources and sinks across regional and global scales. It is just beginning a second phase of model intercomparisons.

In another significant modeling effort, the NASA Ocean Biogeochemical Model (NOBM) was used to assimilate remote sensing data and then evaluate the contributions of four phytoplankton groups to total primary production for the period 1998–2011. Globally, diatoms contributed the most to the total phytoplankton production (~50%). Coccolithophores and chlorophytes each contributed ~20% of the total primary production and cyanobacteria represented about 10% of the total primary production. Interannual variability of primary production by these groups was also assessed over the period 1998–2011. Most interannual variability occurred in the Equatorial Pacific and was associated with climate variability. These results provide a modeling and data assimilation perspective to phytoplankton partitioning of primary production and contribute to our understanding of the dynamics of the carbon cycle in the global oceans. In a third modeling study, Siegel et al. (2014) combined food web models with satellite observations to estimate globally the export of organic carbon from the surface ocean by sinking particles. The results reveal fundamentally different regional-scale patterns in export and export efficiency not found in previous global carbon export assessments. The model reproduces regional-scale particle export field observations and predicts a climatological mean global carbon export from the surface ocean of ~6 Pg C yr^{-1}. Arctic and boreal ecosystem responses to environmental change were investigated in 2014. Several new modeling studies have focused on fluxes of CO_2 and CH_4 from northern high latitude ecosystems and have explored such relationships as permafrost-carbon feedback (Hayes et al., 2014), pan-Arctic spatial heterogeneity in fluxes (Watts et al., 2014; Zhu et al., 2014), and fire and disturbance impacts on ecosystem productivity (Yi et al., 2013). Frost and Epstein (2014) analyzed within-landscape patterns of vegetation change in Siberian tundra to evaluate susceptibility to tall shrub and tree increase using high-resolution satellite photography. They conclude that shrub and tree cover is increasing in tundra ecotones across most of northern Siberia, but that rates of change vary widely regionally and within landscapes. In a related study (Frost et al., 2014), these researchers found positive increases in a vegetation index (i.e., “greening”) in 9 of 11 Siberian landscape types. The Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE), an Earth Venture suborbital mission to collect detailed measurements of important greenhouse gases in the Alaskan Arctic, met its Baseline Science Requirement of at least 500 science flight hours in May 2014. The Terrestrial Ecology program’s planning for its next major field campaign achieved a significant milestone with the public release of the Arctic-Boreal Vulnerability Experiment (ABoVE) Concise Experiment Plan (http://above.nasa.gov/acep.html) in June 2014. The first solicitation for ABoVE research and Science Team membership will be issued in autumn 2014.

Habitat characteristics, including vegetation vertical structure, and relationships with species richness (number of different species) were the focus of significant publications in the past year. Huang et al. (2014) examined the utility of remote sensing measurements of spatial heterogeneity of vegetation height in improving avian richness models across forested ecoregions in the U.S. Height-structured metrics were compared with other habitat metrics for statistical association with richness. Height-structured metrics had the strongest associations with species richness, yielding improved predictive ability for woodland bird groups and forest edge bird groups. The results suggest that measurements of height heterogeneity, beyond canopy height alone, are useful supplements for habitat characterization and richness models of forest bird species. Goetz et al. (2014) used an array of bioclimatic and remotely sensed data sets representing vegetation properties and structure, and other aspects of the physical environment to address breeding bird species richness across the coterminous U.S. at 1 km spatial resolution. In this study vegetation properties were generally the strongest determinants of species richness, whereas bioclimatic and lidar-derived vertical structure metrics were of variable importance and dependent upon the bird group. They suggest the relatively sparse sampling of canopy structure metrics from the satellite lidar sensor may have reduced their importance in this analysis relative to other predictor variables across the study domain. This study strengthened current understanding of bird species-climate-vegetation relationships.

During the past year several new or improved satellite remote sensing data products have been developed and released. In addition to those mentioned above, these include the first satellite lidar-based maps of aboveground carbon stocks for the circumboreal forest biome (Neigh et al., 2013), a consensus land-cover product optimized for studies of biodiversity and ecological models (Tuanmu and Jetz, 2014), and an improved global 8-km vegetation index time series product from the AVHRR sensor (NDVI3g) spanning 1981-2012 (Pinzon and Tucker, 2014). Fundamental remote sensing research, algorithm development and refinement, and exploration of new methods also continue within the program. A few notable examples include work on a chlorophyll-based approach to improved estimates of the fraction of photosynthetically active radiation ($fPAR_{chl}$) and light use efficiency in vegetation (Cheng et al., 2014), lidar-based derivations of leaf area index (LAI; Tang et al., 2014), interferometric SAR (InSAR) algorithms for biomass estimation (Lavalle and Khun, 2014; Treuhaft et al., 2015), and exploration of the use of chlorophyll fluorescence as measured by the NASA OCO-2 satellite for estimating gross primary productivity (Frankenberg et al., 2014). In addition, research is underway to develop and implement algorithms for Suomi NPP VIIRS data products that will establish science-quality continuity data records with Terra and Aqua MODIS data products for carbon cycle and ecosystems.

FY 2014 Annual Performance Indicator	FY 11	FY12	FY13	FY14
ES-14-6: 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

<u>Annual Performance Indicator ES-14-7:</u> 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 and the Japanese Space Agency (JAXA) launched the Global Precipitation Measurement (GPM) mission on Feb 28th, 2014. The mission set the new standard for precipitation measurements from space, improving up the Tropical Rainfall Measuring Mission (TRMM) by covering a larger latitude range (60N to 60S) and using dual frequency radar, which will provide better accuracy of snowfall and light rain precipitation types. It will also continue TRMM legacy of improving the inter-satellite calibration and accuracy of numerous other precipitation satellite products. One of GPM's ground validation activities, Integrated Precipitation and Hydrology Experiment (IPHEx), performed intense observing during May and June of 2014, using multiple airborne radars, to focus on the 4D mapping of precipitation structure to evaluate GPM performance. GPM's level 1 data (e.g. brightness temperatures) were released to the public in June, and level 2 data of precipitation rates were released at the end of July. Going forward, GPM's near real time data availability will enable numerous applications including hurricane monitoring and forecasting, and prediction of flooding, agricultural crop productivity, and freshwater resources.

NASA's Water and Energy cycle focus area has continued to enable better assessment and management of water quantity and quality to accurately predict how the global water cycle evolves in response to climate change. To document our knowledge, the NASA Energy and Water cycle Study (NEWS) has compiled the latest assessments for each of the variables that comprise the water cycle (e.g. precipitation, land and ocean evaporation, etc.). Rodell et al. (2014) have used these data to close the annual global water budget, including transfers between land and ocean basins, with much less than 10% residual. On a more granular basis (monthly or individual continents), the uncertainties were larger, roughly 20%. Unlike most previous attempts at this exercise, the NEWS collection of data sets and techniques relied primarily on satellite observations and enabled the Rodell study to analyze the water budget closure at higher resolutions, both temporally (monthly instead of annual) and spatially (continental and oceanic basins). The enhanced resolution allows others to compare their own regional assessments of water cycle variables and budget closure with those of the NEWS team. While global climate models must have closed water and energy budgets, comparison with the Rodell et al. assessment can point out discrepancies between model climatologies and those seen in observations. These efforts leverage work funded both under the water cycle focus area and others within Earth Science to improve, produce, and analyze data sets of individual water cycle variables (precipitation - Behrangi et al. 2014; Ocean surface fluxes - Clayson et al., 2014 (in revision), Hearty et al., 2014, MERRA Robertson et al., 2014, Wong et al., 2014).
[More information on Rodell et al. can be found at http://gewex.org/2014conf/pdfs/16JulyMattRodellS12_T5.pdf]

Within the water budget, one of the main sources of uncertainty is the flux of water from the ocean surface to the atmosphere. This is not well observed via in situ measures. Satellite data offer alternatives but lack global, full day coverage. NASA investigators have worked together with the Sea Flux project to make numerous advances. (Clayson et al., 2014, in revision). This year's work has helped create a longer Sea Flux dataset, which now span from 1987 to the present. One advance this year has been the identification and correction of a problem with the Earth incidence angle corrections applied to different satellite datasets, reducing errors and creating a more consistent long-term data record of evaporation rates. Another achievement of NASA researchers is creating the ocean evaporation product with a 3-hour temporal resolution. This allows for better inspection of the diurnal cycle and opens new areas of investigation to improve our understanding of this process. All of these improvements have facilitated the evaluation of the NASA Goddard Modeling and Assimilation Office's coupled atmosphere/ocean forecasting system (GEOS-GCM). This project has the potential to enable future Coupled Model Intercomparison Project (CMIP) activities with turbulent fluxes, currently a large void in the CMIP5 evaluation process. Ultimately, this work will complement data from GPM and Aquarius since changes in salinity are related to precipitation minus evaporation.
http://gewex.org/2014conf/pdfs/14JulyClayson.pdf

Evapotranspiration (ET) uncertainties also play a large role in our understanding of the water cycle. NASA supported the first independent assessment of global ET estimates from four common land surface evaporation models. The model estimates were compared to high-quality in situ data from 20 FLUXNET stations. According to the study no one model was best across all biomes (Ershadi et al. 2014). In general, the surface Energy Balance Systems (SEBS) model and a JPL-modified Priestley-Taylor model did well over most biomes, though SEBS was less accurate in areas with tall and heterogeneous canopies. The other two models, single source Penmen-Monteith and advection-aridity, generally performed less well. The outcomes highlight the need for further evaluation of each model's structure and parameterizations to identify sensitivities and their appropriate application to different surface types and conditions.

River discharge also plays a large role in the water cycle. To improve assessment of river discharge and as preparation work for the Surface Water Ocean Topography (SWOT) mission, work focuses on understanding and improving the use of satellite data for river discharge estimation. Gleason and Smith (2014) demonstrated the power of satellite observations, together with an advance in river hydraulic geometry, for regions without in situ measurements by using Landsat thematic mapper images over three different rivers to achieve estimates within 20-30% of river gage observations. Consistent with SWOT's planned instrumentation, Durand et al. (2014) presented an algorithm to solve the shallow water equations to estimate river water surface elevation and slope. The algorithm was tested for the River Severn and for known inflow, provided relatively accurate discharge (10% RMSE). For unknown inflows RMSE increased to 36%. This algorithm's performance could be improved with known river parameters (e.g. bathymetry, roughness). Getirana and Peters-Lidard (2013) combined satellite altimetric observations and land surface modeling to estimate discharge at 475 virtual stations in the Amazon. They tested approaches using a subset of these stations to inform the modeling system (via data assimilation) to get estimates of discharge at the other virtual stations. This work provides evidence that the SWOT discharge algorithm may result in better estimates of river discharge when combined with land-surface modeling then either piece independently.

The amount of water stored in snow is another key aspect of understanding the total water cycle. To explore methods of improving assessment of snow-water equivalents, NASA has completed two years of snow surveys by the Airborne Snow Observatory (ASO; http://aso.jpl.nasa.gov). This project conducted lidar surveys of the Tuolumne Basin during snow-free conditions and throughout the past two snow seasons. The difference provided a high-resolution (meters scale) snow-depth time series. Coincident flights during the winter of an airborne scatterometer collected a parallel time series of snowpack properties. Together, these were used in a model to determine the snow-water equivalent of the snowpack, which can improve the forecasting of snowmelt quantity and timing. These two years of data have generated significant interest from the hydrological community and have increased demand on ASO to fly in other locations. In particular, there are now plans to use ASO in the GPM ground validation experiment in 2015-16 (Olympex) as well as interest from Chile snow researchers and other NASA investigators. This information has also been extremely valuable to decision makers in California during the intense drought since there is demand for water in the snowpack to be used in electric power generation. Robinson et al. (2014) have released and distributed via NSIDC a 25km resolution multi-decadal daily snow cover extent dataset. In addition to being used as part of hydrological studies, this data will be used to critically assess climate model performance in under-evaluated aspects related to cold-land processes.

In August 2013, NASA sponsored a workshop in which the US snow community, with representation from Canadian and European counterparts, met to develop a common vision for snow remote sensing and a future snow mission; Recognizing the need to train the next generation of snow scientists, out of this workshop emerged the idea for two "snow schools", one focused on field techniques and the other focused on modeling. NASA committed to support student travel to these snow schools to provide students with a common core of state-of-the-art training in quantitative snow science. Students worked closely with leading snow scientists and were exposed to a wide range of ongoing snow research activities. Snow science community volunteers organized the multi-day snow schools, coordinating curriculum and logistics, donating field and classroom time, and providing instrumentation and field equipment. Each of the snow schools was followed by a 2-day meeting of the snow science community to further develop a vision for a future snow mission.

Due to their nature, extreme events can significantly impact the global water budget. Studies of extreme events have led to progress in the assessment of how the global water cycle evolves in response to climate change. NEWS initiated innovative integration projects focused on the role of clouds in the climate system, the origins and dynamics of the 2012 Midwestern drought, and the hypothesis of the 2002 global climate shift. As an example, two studies from Kam et al. (2014) have traced back the role of the land surface in drought and differentiated this from larger-scale synoptic patterns. These two studies are able to point to alternative monthly leading indicators for possible drought onset as well as areas of study that might improve drought forecasting. Additionally, Wang et al. (2014) documented the NEWS working group’s investigation of whether the 2012 drought could have been anticipated. They found that there were some important precursors (e.g. Atlantic Ocean conditions and Great Plains low-level jet strength) that gave an early indication of possible drought onset, albeit with limited lead time.

NASA created two different modeling and data assimilation systems for understanding, monitoring, and assessing drought. Now in use by decision makers and the scientific community, they are rooted in NASA’s land surface modeling activity, primarily the Land Data Assimilation Systems (LDAS) and the software used to support land modeling, the Land Information System (LIS). One project has created a land-modeling process that is able to assimilate GRACE data to better characterize the changes in groundwater. This can then be used to create near real-time (as well as retrospective) assessments of the overall water supply compared to a long-term average. These anomaly maps are sent to the National Drought Monitor to augment their knowledge about the changes in groundwater reserves. NASA LIS has now transitioned to NOAA NCEP for use in creating near real-time data sets that are used to drive their land model, which is then used to better inform their weather forecast system. Along these lines, Hirsch et al. (2013) have used these NASA-developed modeling assets to show that different initialization approaches can lead to gains in subseasonal forecast skill of temperature and precipitation. For their particular study, done for southeastern Australia, significant improvement was realized in the forecasting of daily maximum temperatures for up to sixty days into the forecast period. Also Kumar et al. (2014) used LIS in an Observing System Simulation Experiment (OSSE) to evaluate the potential for soil moisture measurements of SMAP to improve a land model's drought and flood risk estimates. The study showed that SMAP is likely to improve not just the model's surface soil moisture but also root zone soil moisture and total runoff resulting in improved risk estimates.

The Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) Earth Ventures project has had a great observing year. The project has fulfilled its minimum mission requirement of airborne acquisitions and released multiple data sets to the Oak Ridge National Laboratory DAAC for wider community usage. In addition to the observations of root-zone soil moisture from the nine biomes, the P-radar was deployed to Alaska this year to retrieve the freeze/thaw profile state of the soil column. This deployment will be repeated in the fall and next spring. This expanded use of the P-band radar will allow others to evaluate if AirMOSS can be used for permafrost studies, especially those planned to support Arctic-Boreal Vulnerability Experiment (ABoVE) campaign. NASA will demonstrate the methods of using P-radar for soil column information making a significant contribution to the European Space Agency Biomass mission.

NASA's Modern-ERA Retrospective Analysis for Research and Applications (MERRA) reanalysis data set continues to be used by investigators to fill in for gaps in our water-cycle observing system. This emphasizes the need to assess the performance of MERRA, both for consistency across satellite systems and for its representation of the different components of the water cycle. NASA investigators (e.g. Robertson et al., 2014) have shown some disparities that appear when comparing the reanalysis system with observation-driven analysis. Unsurprisingly, uncertainties in ocean evaporation are significantly larger than uncertainties in precipitation, such that trends in the reanalysis largely result from changes in satellite observing systems. Additionally, global variation in moisture transport to land shows consistency with signals of El Niño Southern Oscillation (ENSO), although there is still considerable uncertainty in the quantities at longer time scales.

Itterly and Taylor (2014) have used top of the atmosphere flux information to analyze data from both the MERRA and the ERA products. Previously, there have been gaps when using these data to look at the diurnal cycle of the tropics. The study showed smaller temporal discrepancies between observations and MERRA than with ERA-Interim indicative of the timing of each modeling system's cloud fields. Further research is needed to make improvements in the reanalysis model physics, specifically the diurnally forced propagating convection. This is also key because of the potential link with Madden Julian Oscillation initiation.

NASA continues to improve its ability to use remote sensing to better understand inland and coastal water quality. Recent work has documented the absolute calibration performance of Landsat-8's Operational Land Imager (OLI) for the study of inland water and coastal environments, particularly for near-surface concentrations of chlorophyll-a (CHLa) and total suspended solids (TSS) (Pahlevan et al., 2014). This work enables continuity of CHLa and TSS, derived from OLI, with those of other ocean color satellites (e.g. MERIS, MODIS, etc.). Similarly, Kahru et al. (2014) evaluated cross satellite consistency by comparing CHLa estimates from SeaWiFS, MODIS, VIIRS, and MERIS to in situ observations from the California Current region. Over the full range of in situ CHla, all sensors produced a correlation coefficient of about 0.9. However, the accuracy of all satellite estimates diminished at high chlorophyll concentrations due to poor retrieval of remote sensing reflectance.

NASA sponsored “field work” (more appropriately “lake work”) in several areas, notably the Great Lakes and smaller lakes in upstate New York. In situ and aircraft data from Lake Erie are particularly critical this year due to the recent harmful algal bloom that affected the Toledo water supply. Many of the lakes also saw above average ice cover, and NASA researchers took extra observations this summer to understand how the lakes respond to such an event as well as how these processes may be observed and interpreted using remote sensing. Along these lines, NASA held two community workshops in March and May to coalesce interests of the Great Lakes for the overall goal of “establish[ing] a network of regional, national, and international stakeholders to better utilize remote sensing technologies to address Great Lake Issues.” Stakeholders were defined as aquatic remote sensing investigators in addition to managers, regulators, researchers, educators and the general public. They represent the full cross section of governments (i.e. federal, state, local, tribal), educational institutions and non-profit organizations.

FY 2014 Annual Performance Indicator	FY 11	FY12	FY13	FY14
ES-14-7: 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

<u>Annual Performance Indicator ES-14-9</u>: 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.

A major area of emphasis and progress in 2014 for the Climate Focus Area (CFA) was the research and program organization surrounding the problem of rising global sea level. In addition to work across the three program areas in Climate (Physical Oceanography, Cryospheric Sciences, and Global Modeling) the CFA is working with Solid Earth and Earth Science Data Systems to establish a NASA Sea Level Change Team. The coordinated effort seeks to reduce uncertainty in sea level rise estimates using the extensive NASA technical expertise in observing ocean surface topography, ice sheets, land motion, hydrology, and tides and knowledge of such processes as ocean thermal expansion, ice sheet melt, isostatic rebound, anthropogenic water impound, wind variability, and changing ocean circulation. The area is rich in NASA scientific results with science progressing rapidly in many areas. Many of the accomplishments and publications cited in this report contribute to our understanding of sea level and the N-SLCT is expected to integrate and synthesize much of this knowledge over the coming three years.

The largest uncertainty in projections of future sea-level change results from the potentially changing dynamical ice discharge from Antarctica. Basal ice-shelf melting induced by a warming ocean has been identified as a major cause for additional ice flow across the grounding line. NASA-funded investigators have estimated the uncertainty range of future ice discharge from Antarctica by combining uncertainty in the climatic forcing, the oceanic response and the ice-sheet model response (Levermann et al 2014). The resulting uncertainty range for the historic Antarctic contribution to global sea-level rise from 1992 to 2011 agreed with the observed contribution for this period when using the three ice-sheet models with an explicit representation of ice-shelf dynamics and account for the time-delayed warming of the oceanic subsurface compared to the surface air temperature.

Ice shelves play key roles in stabilizing Antarctica's ice sheets, maintaining its high albedo and returning freshwater to the Southern Ocean. Improved data sets of ice shelf draft and underlying bathymetry are important for assessing ocean–ice interactions and modeling ice response to climate change. The long, narrow Abbot Ice Shelf, south of Thurston Island, produces a large volume of meltwater, but is close to being in overall mass balance. While the ice shelf is presently in equilibrium, recent work (Cochran et al 2014) indicates sensitivity to changes in characteristics of the ocean surface and deep waters.

Mass loss from the Greenland ice sheet contributes significantly to present sea level rise. High meltwater runoff is responsible for half of Greenland's mass loss. Surface melt has been spreading and intensifying in Greenland (Forster et al 2014), with the highest ever surface area melt and runoff recorded in 2012. How surface meltwater reaches the ocean, and how fast it does so, however, is poorly understood. The bed topography beneath the Greenland ice sheet controls the flow of ice and its discharge into the ocean. Outlet glaciers move through a set of narrow valleys, whose detailed geometry is poorly known, especially along the southern coasts. As a result, the contribution of the Greenland ice sheet and its glaciers to sea-level change in the coming century is uncertain. Recent work (Morlighem et al 2014) has inferred ice thickness and bed topography along the entire periphery of the Greenland ice sheet at an unprecedented level of spatial detail and precision. They detected widespread ice-covered valleys that extend significantly deeper below sea level and farther inland than previously thought. Their findings imply that the outlet glaciers of Greenland, and the ice sheet as a whole, are probably more vulnerable to ocean thermal forcing and peripheral thinning than inferred previously from existing numerical ice-sheet models.

The long time series of Quikscat winds have contributed to the evaluation of numerical models. Along with SST and SSH data , Quikscat winds have elucidated properties ('self induced Ekman pumping') of mesoscale eddies, intraseasonal (30-90 day scales) variability in the Indian Ocean, the 'beta plume' in the Hawaiian Lee Countercurrent, and the effect of easterly winds through the gaps of Central America on cyclogenesis in the Pacific ocean. Quikscat data have been shown them to be useful for sea ice studies, in addition to their main application for ocean winds.

The salinity data from the Aquarius mission has allowed estimation of surface alkalinity with direct significance for understanding ocean acidification, to better forecast El Niño events, to see the competing effects of ocean advection and evaporation-minus-precipitation in the Madden-Julian oscillation, and to model the relationship between salinity and ocean color. Data from the Salinity Processes in the Upper-ocean Regional Studies (SPURS-1) field experiment in the North Atlantic and Aquarius revealed the relative roles of eddies vs. wind ('Ekman' current) in transporting freshwater into regions of strong evaporation. Planning is underway for a SPURS-2 field program beginning mid-CY2016 in the eastern tropical North Pacific to study ocean salinity processes in a high precipitation regime.

In 2013, for the first time, Operation IceBridge (OIB) conducted a deployment in the Arctic to collect altimetry data over sea ice and the Greenland ice sheet during the annual melt season. For three weeks, between October and November 2013, NASA's C-130 aircraft flew nine science missions with the Land, Vegetation and Ice Sensor (LVIS) and its smaller version, LVIS-GH, designed for the unpiloted Global Hawk (GH) platform. The data collected will help with the interpretation of altimetry data from future satellite missions, such as ICESat-2, during this challenging time of year, when ice surfaces undergo significant change.

NASA initiated a new airborne science program this year, designed to study the effect of sea ice retreat on Arctic climate. The Arctic Radiation – IceBridge Sea&Ice Experiment (ARISE) conducted flights during the peak summer melt in September 2014. It is the first Arctic airborne campaign designed to take simultaneous measurements of ice, clouds and the levels of incoming and outgoing radiation, the balance of which determines the degree of climate warming. The team flew aboard NASA's C-130 aircraft from Eielson Air Force Base near Fairbanks, Alaska, and targeted different cloud types and surface conditions, such as open water, land ice and sea ice.

Over decadal timescales, internal ocean variability obscures the long-term sea-level change, making it difficult to assess the effect of anthropogenic warming on sea level. Recent work (Hamilington et al. 2014) to uncover the sea-level rise pattern in the tropical Pacific Ocean associated with anthropogenic warming is a good example of necessary physical oceanographic work required to untangle elements of the sea level rise story. The sea-level variability in the tropical Pacific Ocean associated with the Pacific Decadal Oscillation is estimated and removed from the regional sea-level trends computed from satellite altimetry measurements over the past two decades. The resulting pattern of regional sea-level rise is explained in part by warming in the tropical Indian Ocean, which has been attributed to anthropogenic warming.

In addition to the focus on sea level change, NASA continues to focus on increasing comprehensiveness and interactivity in its large scale Earth system modeling efforts, as well as funding related efforts to develop model parameterizations in anticipation for future implementation, and process studies which utilize the models in conjunction with observations.

The GISS Model E2, which was used extensively to produce output for the Coupled Model Intercomparison Project, version 5 (CMIP5) [Miller et al., 2014], was comprehensively evaluated with observations in order to establish the representativeness of the model simulations. The evaluation found significant sensitivity of model base climate and variability to the choice of ocean module in the code, but less sensitivity to changes in the representation of atmospheric composition and aerosol indirect effects [Schmidt et al., 2014]. The comprehensiveness of the GISS Model E was improved in the past year by coupling the model to a newly developed version of the Parallel Ice Sheet Model (PISM), a difficult procedure requiring close attention to mass and energy conservation considerations as well as difficulties caused by the resolution differences between the GCM gridsize and the higher resolution of the ice sheet model needed to properly represent outlet glaciers [Fischer et al., 2014]. Ice sheet coupling to the GEOS 5 GCM, the other global-scale GCM funded by NASA, was also accomplished although the technique employed was different due to differing representations of land surface in GEOS 5 relative to Model E [Cullather et al., 2014].

Model E also saw other significant improvements, including a parameterization of convective downdraft cold pools with the intent of better representation of mesoscale convective systems. Work was done to investigate and improve the model representation of Madden-Julian Oscillation (MJO) events, including basic process studies. One result of this effort was new understanding of the differences between propagating and non-propagating MJO events, finding a strong connection between propagation and the strength of dry anomalies over the eastern Maritime Continent and the Western Pacific [Kim et al., 2014]. The representation of the natural ocean carbon cycle was also investigated and improved, using the NOBM connected to Model E versions with different codes. These studies found that carbon export is very sensitive to remineralization rate changes in the frontal regions of the subtropical gyres and at the Equator [Romanou et al., 2014].

The GEOS5 modeling system has also been significantly improved in the past year. It forms the basis of a chemistry-climate modeling capability which in the past year has been expanded to include coupling to the modeling system's ocean component, creating an Atmosphere/Ocean Chemistry Climate Model, or AO-CCM. Tropical non-orographic gravity wave drag sources were included in the code, leading to the generation of a realistic stratospheric quasi-biennial oscillation (QBO) in the tropical zonal wind, affecting many aspects of the modeled stratospheric dynamics and trace gas distributions [Hurwitz et al., 2013]. The non-coupled version was involved this year in an investigation to understand how current observations can be used to constrain projections of future changes in stratospheric ozone concentrations. It was found that only some diagnostics are good indicators of inter-model differences in projections of stratospheric ozone. If the relationship between those diagnostics and the projections can be established strongly, there is a good basis for utilizing current observations to constrain projection uncertainty [Douglass et al., 2014].

In addition during the past year the NASA Ocean Biogeochemical Model (NOBM) was completely integrated into the GEOS 5 modeling system, providing a representation of ocean biology in a coupled ocean framework. This will allow expanded investigations of feedbacks between ocean biology and the physical Earth system. Added to the modeling system was the GEOS-Chem grid-independent CTM. This addition creates a strong link between the GEOS-Chem CTM, which is developed and maintained at Harvard University, and the Goddard Modeling and Assimilation Office (GMAO) at NASA GSFC. The advantage of such an arrangement is that it allows for rapid synchronization of code developments pioneered at Harvard into the GEOS 5 system, providing benefits for all users. In addition, a new emissions component was added [Keller et al., 2014].

Also incorporated into the GEOS 5 modeling system was a new parameterization of the planetary boundary layer, based on a combination of the more traditional eddy diffusivity and mass flux parameterizations. This new combined ESMF scheme has been subsequently integrated with a cloud microphysics scheme in a single column model, allowing both non-precipitating and precipitating convection to be represented with a single parameterization.

Overall in 2014 CFA has seen increasing interdisciplinary work and more interagency and international collaboration. It is expected that significant and visible progress will be made in a number of areas in the next two years, but especially highlighting sea level science.
The efforts represented in this Annual Performance Indicator document substantive contributions to better understand the roles and interactions of the ocean, atmosphere, land, and ice in the climate system. There are tangible contributions to better forecasting the recovery of stratospheric ozone and sea-level rise. GISS contributions to CMIP5 and, by inference, to IPCC reports are notable. How the model development contributes to broader goals “to predict climate changes,” and how the observing program informs model development needs to be better substantiated.

FY 2014 Annual Performance Indicator	FY 11	FY12	FY13	FY14
ES-14-9: 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. Progress relative to the objectives in NASA's 2014 Science Plan will be evaluated by external expert review.	Green	Green	Green	Green

<u>Annual Performance Indicator ES-14-11:</u> 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) has seen very significant progress in each of the three interrelated program elements (space geodesy, natural hazards and Earth's interior) during FY2014 toward the objectives of 2.1.6. Main accomplishments involve the **space geodesy program, geodetic remote sensing including advancements in DEM generation, advances in low latency geodetic techniques in support of infrastructure for disaster warning, and geopotential field measurement and analysis**.

1. *The Space Geodesy Program Element:*

NASA's ESI has organized the tasks of Space Geodesy Program (SGP) at GSFC and JPL under a single consolidated management structure in order to cultivate a more coherent and vibrant development of Space Geodetic science within the agency, the nation, and internationally.

During the past year SGP, in cooperation with many international partners, continued to play a key role in establishing, maintaining, and operating global geodetic networks which NASA contributes nearly 40% to the global infrastructure. These networks include: Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and the Global Navigation Satellite System (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) network of ground stations. In fiscal year 2014, NASA continued to operate the geodetic observing stations and generate relevant data products and services that are provided worldwide through the International Laser Ranging Service (ILRS), the International VLBI Service for Geodesy and Astrometry (IVS), the International GNSS Service (IGS), and the International DORIS Service (IDS), under the umbrella of the GGOS.

A new record for the NASA SLR Network was set in June 2014 with over 6000 total pass segments recorded that month with all 8 stations continuing to perform well. While NASA's SLR station in Australia (MOBLAS-5) remains to be the highest performing station, NASA's station in South Africa (MOBLAS-6) contributed with a record month of 1153 pass segments. Even though the failure risk continues to increase for the aging network, this risk was mitigated by almost seamless depot level maintenance on several sites, including the South Africa, Tahiti, Maryland, and California stations. The NASA ILRS Analysis Center also continued daily and weekly products of analysis and combination for the ILRS, along with other service-related tasks such as verifying/validating new sites (Russian, Korean etc.) and daily quality control of systematics for all ILRS stations.

This spring SGP completed a site selection study for the deployment of new multitechnique core geodetic observatories: McDonald Observatory in Texas was selected for the western US site and NASA's Kokee Park Geophysical Observatory (KPGO) on Kauai along with the Haleakala Observatory on Maui were selected for the Pacific stations. These new stations are expected to be operational in 2017. Discussions are underway with existing and potential international partners (both through the GGOS and bilaterally) for the development of the new NASA network.

This year NASA also established a partnership with the U.S. Naval Observatory to start work on the replacement of the old VLBI instrument at KPGO to the new NASA VLBI2010 system, similar to the one operating at NASA's Goddard Geophysical and Astronomical Observatory in Greenbelt, MD. The KPGO antenna successfully passed its Critical Design Review in July 2014 and is expected to become operational in 2016.

The Crustal Dynamics Data Information System (CDDIS) distributed over 500 million files (over 80 Tbytes in volume) over the first 10.5 months in FY14 and remained operational during the government shutdown. On average, these data were distributed to 13,000 distinct hosts per month. This is a 50% increase in total volume distributed over the same time period in FY13. An additional 2 Tbytes of data from 19 million files were added to the archive thus far in FY14.

The International Earth Rotation and Reference Systems Service (IERS) has certified JPL as an ITRF Combination Center, one of only three worldwide and the only one in the US. The Terrestrial Reference Frame Combination Center (TRF CC) at JPL was funded to produce products to be incorporated into the realization of the next International TRF (ITRF). NASA's Jet Propulsion Laboratory (JPL) hosts the Space Geodesy Program's International Coordination and Partnership Office (ICPO). The ICPO ensures that NASA's interests are properly represented in key organizations and that international cooperation is secured when needed to meet NASA's space geodesy objectives. The ICPO was instrumental in the preparation and delivery of the GGOS Strategic Plan 2014 – 2017 in this reporting period.

<u>*2. The Natural Hazards Program Element:*</u>

The natural hazards program element considers geohazards including earthquakes, volcanoes, landslides, other surface deformation, tsunami, and to a lesser extent inundation associated with coastal storm surge and heavy rainfall. NASA works closely with other agencies such as USGS, NOAA and DHS through joint research and data exchange. A major programmatic focus of the natural hazards program element is related to improved access to and use of near real time and real time geodetic data such as GNSS and interferometric synthetic aperture radar (InSAR) as well as thermal data.

Real Time GNSS and Disaster Response:

NASA continues to build upon the significant demonstration the capability and potential of real time GNSS ground networks. GDGPS provides real time positioning information to a host of end users including the essential precision navigation for repeat pass interferometry of the UAVSAR whose mission is dependent upon accurate real time navigation. (website: http://www.gdgps.net/system-desc/index.html)

NASA continued developing an Indo-Pacific earthquake and tsunami early warning system that leverages existing GNSS network infrastructure to provide advanced warning to communities that are at greatest risk. The Real-time Earthquake Analysis for Disaster Mitigation Network (READI) advances over the past year include the integration of GPS and accelerometer (for strong-motion data) to estimate seismogeodetic waveforms (Crowell et al., 2013; Geng et al., 2013; Yue et al.; 2013; and Protti et al., 2014). The strength of the seismogeodetic approach is that it may be possible to estimate the final magnitude of an earthquake well before the rupture is complete. Current approaches that utilize accelerometer data that saturate in earthquakes greater than *M* 7, thereby taking longer to estimate the earthquakes magnitude.

Recently READI's tsunami early warning research examined source models obtained from newly developed algorithms and multisensor data to demonstrate the ability of source models determined from land-based coseismic data from the combination of GPS and strong-motion sensors to forecast near-source tsunamis. Melgar and Bock (2013) also demonstrate that rapid ingestion of offshore shallow water (100–1000 m) wave gauge data substantially improves the earthquake source and tsunami forecast. Their results indicate potential benefits of shallow water wave gauges coupled with land-based geophysical sensors can, in the future, provide enough information to issue timely and accurate forecasts of tsunami intensity immediately or shortly after rupture initiation of large earthquakes.

The Advanced Rapid Imaging and Analysis project (ARIA) is an ESI sponsored joint JPL/Caltech effort to automate synthetic aperture radar (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. Through its collaboration with the Italian Space Agency (ASI), the ARIA team has been implementing its cloud-enabled SAR analysis data system using COSMO-Skymed (CSK) X-band SAR data. The collaboration and data access agreements with ASI enabled the ARIA team to provide a near real time damage proxy map for Typhoon Haiyan, the storm that devastated the Philippines in November 2013 (http://photojournal.jpl.nasa.gov/catalog/ PIA17687) as well as a flooding map for areas of Sardinia hard hit by Cyclone Cleopatra (http://photojournal.jpl.nasa.gov/catalog/PIA17738). The ARIA team also generated CSK InSAR hazard response products for regions of volcanic unrest across the globe including: Kilauea Volcano, Hawaii; Barbadunga Volcano, Iceland; Kelud Volcano, Java; and Copahue Volcano, Chile. One of the largest earthquake response activities in the last year was for the M6.0 South Napa earthquake on August 24, 2014 (http://photojournal.jpl.nasa.gov/catalog/PIA18798), where the team provided GPS measurements of the coseismic deformation within 2 days and a coseismic intereferogram within 4 days after the earthquake. After its release, field teams used the CSK coseismic interferogram immediately to identify additional surface ruptures.

The ARIA team extended its automatic GPS processing to several tectonic networks, including GPS stations in the Central Andean Tectonic Observatory (CAnTO) network at the time of the M 8.0 Pisagua earthquake on April 1, 2014. This effort not only provided geodetic coseismic offsets measurements, but with additional analysis and regional data, the ARIA team has identified possible transient deformation that preceded the mainshock. The team generated earthquake data products for the M5.1 La Habra, California earthquake on March 28, 2014 (GPS and InSAR, Fielding et al., 2014, in press) and M6.8 Ferndale, CA earthquake on March 10, 2014 (GPS). The ARIA team also participated in two state earthquake exercises in California and one national level exercise with FEMA to begin coordinating with the emergency response communities and providing products to the end user communities.

Earthquake Forecasting:

NASA supports modeling and analysis efforts that utilize geodetic, geodetic imaging, and geopotential field measurement strategies. Our cooperative research agreement continues to support Quakefinder, LLC in the study and measurement of identified ULF signals associated with stress changes and fault motions. Quakefinder analysis reports that it identified 8 earthquakes with identifiable electromagnetic precursors, but had trouble conclusively identifying the recent Napa Valley earthquake. They are currently working with Amazon Cloud services and TopCoder to setup a website based contest to analyze portions of their data achieve. This year NASA continued to work with Quakefinder to make all of these datasets readily available to the research community and formalize any probabilistic short-term forecasts (or predictions) of earthquakes in the framework of the SCEC Collaboratory for the Study of Earthquake Predictability (CSEP).

UAVSAR:

The airborne UAVSAR (http://uavsar.jpl.nasa.gov/) 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 Gulfstream-III and also capable of flying on the Global Hawk.

Prior to FY14, the UAVSAR project went through the development, test, and science demonstration phases. The instrument has been very reliable and well calibrated; radar operation from flight planning to data acquisition has been streamlined and is robust. The project has been routinely delivering polarimetric SAR data products with a short latency (2-3 weeks). However, successful acquisition and processing of data for airborne repeat-pass interferometry (RPI) for geodetic applications continued to be a challenge and was the dominant mode requested for science investigations. In addition to small RPI data delivery throughput, the delivery latency was also very long, from months to over a year after data acquisition, which resulted in a huge processing backlog and frustrated comprehensive scientific analysis. Steps were successfully taken in FY14 to radically improve the following areas: improve the successful acquisition rate of RPI data (in terms of aircraft trajectory) to at least 90%, develop a browse RPI product with a delivery latency goal of 4 weeks or less, improve the refined RPI product latency to 6 weeks or less upon receipt of processing request, develop a co-registered single look complex (SLC) stack product where PIs can use for time series analysis, and finally, clear all processing backlog by the end of FY14.

The dramatically improved production processing latency was put to test in late August 2014 when the UAVSAR project was called to aid rapid response efforts shortly after the M 6.0 South Napa earthquake in determining faulting and assessing levee/aqueduct damage. The project was able to deliver browse RPI products of all flown flight lines within 48 hours post-flight and began delivering refined interferometric products within 4 days post-flight. With browse data, the project was able to provide information to the California Department of Water Resources about crustal deformation along the San Pablo Bay shoreline quickly in support of their levee response activities and to the USGS to direct their ground survey crews. The UAVSAR images showed exquisite slip details around the epicenter of the quake in areas where the X-band COSMO-Skymed data released earlier in the week were completely decorrelated and unusable. The results agreed with ground surveys of movement on the main fault and provided much more comprehensive information about the movement that occurred across the region.

During the one year time period from August 1, 2013 to July 31, 2014, UAVSAR conducted 67 flights with 674 successfully acquired flight lines to support 16 principal investigators and acquired over 16TB of raw data. Major deployments and objectives during this one year period included: (1) volcanic deformation studies of Japan, Hawaii, Central and South America, (2) deformation associated with plate boundaries in California along the San Andreas, Hayward and associated faults in Baja California, (3) surface deformation associated with Gulf Coast subsidence, (4) surface deformation associated with levee conditions in the Sacramento and Mississippi deltas, (5) landslide mechanics study in Slumgullion, Colorado and Arizona (6) environmental impacts of the Gulf oil spill, (6) SMAP soil moisture cal/val in the Midwest and Argentina, (7) glacier study in Chile, and (8) temperate glacier study in Iceland.

UAVSAR conducted two engineering demonstration flights of the L-band radar onboard the Global Hawk in December 2013. The project successfully acquired data during the 6-hour flight in California’s Eastern Sierra while the 18-hour Canada flight allowed us to identify instrument communication, data recording rate, and thermal management issues. These issues are being addressed this summer and more engineering demonstration flights will be scheduled in the winter of 2014/2015.

UAVSAR continued to play a major role in acquiring data over SMAP study sites to support SMAP mission’s validation of soil moisture retrieval algorithms and products. UAVSAR data improved the understanding of glacier seasonal dynamics based on Iceland data; these studies also help inform planning for the NISAR mission. UAVSAR observations documented triggered slip on faults in the Salton Trough associated with the

2010 M7.2 El Mayor-Cucapah earthquake (Donnellan, et al., 2014). UAVSAR observations captured major sinkhole precursory movement of up to 0.25 m in the Louisiana Gulf Coast that occurred at least one month prior to sinkhole formation and covered a much larger area (Jones and Blom, 2013). UAVSAR observations provided a unique view of the short time glacier deformation (<4 days) in Chile, providing scientists at USGS and Chilean government with evidence that glaciers are moving significantly faster velocities and there is more widespread glacier retreat, which has important consequences for water resource management in Andean countries.

Science results based on UAVSAR data were published in 17 refereed journal papers and presented at major international conferences, including 11 papers at AGU in December 2013, 5 papers at EUSAR in June 2014, and 9 papers at IGARSS 2014.

By Executive Order on September 23, 2014 the White House announced release of the SRTM-2 30-m global data set over the next year starting immediately with much of Africa as part of an initiative on Climate-Resilient International Development. The SRTM mission in 2000 led to the development of a global DEM at 30-m and 90-m postings that quickly became the benchmark standard for seamless global coverage. The main products finished by the National Geospatial-Intelligence Agency (NGA) have been publicly available for over a decade at 90-m, but the 30-m previously restricted for areas outside of CONUS. An improved data set, known as NASADEM, is the result of a complete reprocessing of SRTM using updated algorithms to compensate for known systematic errors in combination with ICESat and Aster data. The products will be released over the next year or two in continental blocks.

3. The Earth Interior Program Element:

This program seeks to understand the dynamics of the Earth's interior via three primary observation techniques. Space Geodesy, Gravity Field models, and Geomagnetic Observations.

NASA funded geohazards research at NASA GSFC quantified gravity changes after recent great earthquakes present within the 10-year-long time-series of monthly GRACE gravity fields. They include the *2004 Sumatra-Andaman*, *2007 Southern Sumatra*, *2007 & 2008 Kuril i*slands, *2010 Maule (Chile)*, *2011 Tohoku-Oki (Japan)*, *2012 Indian Ocean (strike-slip)*, and *2013 Sea of Okhotsk* earthquakes. The global gravity fields are disturbed by episodic rupture as well as gradual relaxation processes associated with these earthquakes. Spatially- and temporally-continuous observations of these events from the Gravity Recovery and Climate Experiment (GRACE) constrain not only the earthquake source mechanism but also the rheological structure of the Earth. Han et al. (2014) showed that post-seismic gravity variation is best modeled by the biviscous relaxation with a transient and steady state viscosity of 10^{18} and 10^{19} Pa s, respectively, for the asthenosphere. This is useful in the development of better post-seismic relaxation models. The results from these studies are also useful to correct the GRACE data products for climate and hydrological studies.

In the 2013-2014 reporting period, ESI focus area funded several research studies investigating the Earth's Interior using geodetic gravity measurements from the Gravity Recovery and Climate Experiment (GRACE). These studies have increased our knowledge on how the shape of the earth changes due to variations in surface loading, groundwater storage, and allows for the refinement of viscoelastic Glacial Isostatic Adjustment (GIA) models. The results of one of these ESI funded university research grants examined the significant drop in global sea level that occurred in 2011 (Fasullo et al. 2013). This drop was unprecedented in the altimeter era and concurrent with an exceptionally strong La Niña. Grace data showed a surface mass anomaly in Australia that was caused by large precipitation anomalies. The continent's unique surface hydrology, which includes expansive arheic and endorheic basins, impeded runoff to the ocean and therefore, Australia has a key role in addressing sea level variability.

A study using GRACE data examined regional-scale mass balances for 25 drainage basins of the Antarctic Ice Sheet (AIS) for the time period January 2003 to September 2012. Satellite gravimetry estimates of the AIS mass balance are strongly influenced by mass movement in the Earth interior caused by ice advance and retreat during the last glacial cycle. The researchers developed an improved GIA estimate for Antarctica using newly available GPS uplift rates, allowing us to more accurately separate GIA-induced trends in the GRACE gravity fields from those caused by current imbalances of the AIS. This revised GIA estimate is considerably lower than previous predictions, yielding an estimate of apparent mass change of 53 ± 18 Gt yr^{-1}. Therefore, the AIS mass balance of -114 ± 23 Gt yr^{-1} is less negative than previous GRACE estimates. The northern Antarctic Peninsula and the Amundsen Sea sector exhibit the largest mass loss (-26 ± 3 Gt yr^{-1} and -127 ± 7 Gt yr^{-1}, respectively). In contrast, East Antarctica exhibits a slightly positive mass balance (26 ± 13 Gt yr^{-1}), which is, however, mostly the consequence of compensating mass anomalies in Dronning Maud and Enderby Land (positive) and Wilkes and George V Land (negative) due to interannual accumulation variations. In total, 6% of the area constitutes about half the AIS imbalance, contributing 151 ± 7 Gt yr^{-1} (ca. 0.4 mm yr^{-1}) to global mean sea-level change.

Another study by Lange et al. (2014) used thirty-one GPS geodetic measurements of crustal uplift in southernmost South America to estimate extraordinarily high trend rates (> 35 mm/yr) in the north-central part of the Southern Patagonian Icefield. These trends have a coherent pattern, motivating a refined viscoelastic glacial isostatic adjustment model to explain the observations. Two end-member models provide good fits: both require a lithospheric thickness of 36.5 ± 5.3 km. However, one end-member has a mantle viscosity near $\eta = 1.6 \times 10^{18}$ Pa s and an ice collapse rate from the Little Ice Age (LIA) maximum comparable to a lowest recent estimate of 1995–2012 ice loss at about −11 Gt/yr. In contrast, the other end-member has much larger viscosity: $\eta = 8.0 \times 10^{18}$ Pa s, half the post–LIA collapse rate, and a steadily rising loss rate in the twentieth century after AD 1943, reaching −25.9 Gt/yr during 1995–2012.

NASA funded researchers, Tyler and Kuang (2014), used a simplified model to examine the existence of a stably stratified layer below the core-mantle boundary. The study "suggests that one must accept either (1) that tidal forces resonantly excite core flow and this is predicted by a simple model or (2) that either the independent estimate or the dynamical model does not accurately portray the core surface layer and there has simply been an unlikely coincidence between three estimates of a stratification parameter which would otherwise have a broad plausible range."

FY 2014 Annual Performance Indicator	FY 11	FY12	FY13	FY14
ES-14-11: 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