EARTH SCIENCE DIVISION

Strategic Goal 2: Expand scientific understanding of the Earth and the universe in which we live.

Outcome 2.1: Advance Earth system science to meet the challenges of climate and environmental change.

Objective 2.1.1: Progress in understanding and improving predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition.

In the past year, NASA researchers participated in multiple Earth Venture-1 funded suborbital missions, including the Airborne Tropical Tropopause Experiment (ATTREX), Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ), and the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE). Initial results from ATTREX provide clear evidence for two distinct classes of thin cirrus in the Tropical Tropopause Layer. The predominance of the low-ice concentration cirrus near the tropical tropopause may permit considerably more water to pass through the cold trap into the stratosphere than is typically assumed in models. Preliminary analyses of DISCOVER-AQ observations over the Baltimore-Washington corridor suggest that the expectation of a well-mixed boundary layer is often incorrect and that each pollutant can have a different vertical distribution. CARVE, which conducted its first science flights during May and June 2012, is designed to quantify correlations between atmospheric concentrations of CO_2 and CH_4 with surface-atmosphere carbon fluxes and surface state control variables (soil moisture, freeze-thaw state, inundation state, surface soil temperature) and elucidate the sensitivities of Arctic carbon cycle processes to climate change.

NASA researchers participated in several internationally coordinated activities to advance the state of knowledge of atmospheric ozone measurements and theory. Under the auspices of the World Climate Research Program (WCRP) Stratosphere-troposphere Processes And their Role in Climate (SPARC) program, researchers are assessing and extending the current knowledge and understanding about measurements of the vertical distribution of ozone, with the aim of providing input to the next World Meteorological Organization Scientific Assessment of Ozone Depletion anticipated for 2014. The SPARC Reassessment of Lifetimes of Long-Lived Atmospheric Trace Gas Lifetime Crucial to Ozone Depletion and Climate Change, co-led by NASA researchers, is reviewing estimates of the lifetimes of key atmospheric molecules crucial to understanding current and future atmospheric concentrations of ozone depleting substances (ODSs) and greenhouse gases (GHGs).

Using measurements from MLS and OMI, it was found that the chemical ozone destruction over the Arctic in early 2011 was—for the first time in the observational record—comparable to that in the Antarctic ozone hole. Significant Arctic ozone loss was found to occur even with temperatures much milder than those in the Antarctic. However, it is still difficult to predict when such severe Arctic ozone depletion may be matched or exceeded.

Numerous studies across the Focus Area continue to assess and improve the predictive capability of models for changes in composition, climate forcing and air quality. For example, multiple data sets, mostly from satellite observations (TES and MLS), were used to evaluate the performance of the Weather Research and Forecasting model with Chemistry (WRF-Chem) in simulating the distribution and evolution of aerosol, clouds, precipitation and chemistry during the dry season in South America. The study demonstrated that satellite data are valuable to the evaluation of regional model simulations for climatologically important processes such as deep convection and biomass burning, especially in regions with little in situ observation. Another study evaluated the representation of processes controlling tropical and subtropical tropospheric relative humidity (RH) in atmospheric GCMs. Observations of the water vapor isotopic ratio from several satellite data sets, including TES, ACE, MIPAS, and SCIAMACHY, were used in the analysis. Comparing seven isotopic GCMs suggested that the moist bias found in many GCMs in the mid and upper troposphere most frequently results from an excessive diffusion during vertical water vapor transport.

The value of using multiple space-based data sets and models was highlighted in an analysis using observations from CALIOP, MLS, AIRS, and ESA MIPAS, together with the GEOS-5 data assimilation system to investigate the development of polar stratospheric clouds (PSCs) and the gas-phase nitric acid distribution in the early 2008 Antarctic winter. It was found that for liquid PSCs the uptake of HNO_3 followed the theoretical equilibrium curve for supercooled ternary solutions, but at temperatures about 1 K lower as determined from GEOS-5.

In order to track publications from Focus Area funded projects in a more quantitative manner, an Earth Science Publications website was established this year. Publications can be viewed in a variety of ways, including by Program area, mission, and author. While this database is still being populated, preliminary results reveal that at least 71 papers were published in 2011 and 52 papers in 2012.

FY 2011 Annual Performance Goal	FY 09	FY10	FY11	FY12
2.1.1.1: ES-11-1: Demonstrate planned progress in understanding and improving predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition. Progress relative to the objectives in NASA's 2010 Science Plan will be evaluated by external expert review.	Green	Green	Green	Green

Objective 2.1.2: Progress in enabling improved predictive capability for weather and extreme weather events.

AIRS radiances continue to be successfully assimilated into the major numerical weather prediction centers around the world such as the European Centre for Medium-range Weather Forecasts (ECMWF), the National Centers for Environmental Prediction (NCEP), the United Kingdom Meteorological Office (UKMO) and the United States Navy Operational Global Atmospheric Prediction System (NOGAPS). Observation sensitivity studies emanating from these different centers as well as from NASA's Global Modeling and Assimilation Office (GMAO) continue to show, not only that AIRS is absolutely essential for weather forecast quality, but also that AIRS is the single most important space-based instrument in improving weather prediction quality.

NASA sponsored research continued to gain new insight into weather and extreme-weather events by the utilization of data obtained from a variety of satellite platforms (GOES, TRMM, Aqua, Terra, CloudSat, and CALIPSO).

Several studies have examined the robust signatures of internal gravity waves in AIRS data. AIRS has been used to not only understand the physics of gravity waves and its interactions with the large scale weather, but also to develop and improve more sophisticated gravity wave parameterizations for weather and climate prediction models.

AIRS is increasingly being used to obtain a deeper understanding of the physics of the atmospheric boundary layer. It was shown that AIRS is capable of producing a realistic structure of temperature and water vapor in the boundary layer over the subtropical oceanic regions covered with shallow cumulus. AIRS has also been shown to be a particularly useful tool to understand the interactions between the key cloudy boundary layer characteristics and the climatological large scale circulation. This is absolutely essential to understand cloud-climate feedbacks, which are considered by the Intergovernmental Panel on Climate Change (IPCC) as the main reason for uncertainty in current climate change projections.

NASA's Short-term Prediction Research and Transition (SPoRT) Center continues to transition experimental satellite data and forecast products to NOAA's National Weather Service (NWS) forecast offices and NOAA/NWS/National Centers for Environmental Prediction, to advance current techniques for weather analysis and forecasting while also preparing forecasters for the next generation of geostationary and polar-orbiting satellite capabilities. SPoRT leverages NASA satellite instrumentation and high resolution weather forecast models to test and evaluate new techniques that improve the representation of sea surface temperatures, vertical profiles of temperature and moisture, vegetation, and soil characteristics with applications to short-term forecasts (0-48 h) of severe weather, and other hydrologic applications such as drought monitoring. NASA

collaborates with the NOAA GOES-R and Joint Polar Satellite System (JPSS) Proving Grounds to demonstrate future forecasting capabilities by using MODIS data from Terra and Aqua, and more recently, the VIIRS instrument launched aboard the Suomi National Polar Orbiting Partnership (S-NPP) in October 2011. In addition, SPoRT's expertise in atmospheric electricity advances the use of total lightning data available from ground networks throughout the United States, in preparation for the Geostationary Lightning Mapping instrument aboard GOES-R. It is expected that this type of lightning data will improve our ability to predict severe weather and increase forecast lead time. Furthermore, SPoRT's collaborations with NOAA have integrated NASA observations into the next generation decision support system "AWIPS II" system used by NWS forecasters in analysis and emergency response applications. SPoRT currently partners with 23forecast offices throughout the United States in addition to 6 National Centers and NOAA test beds, providing valuable forecaster feedback to improve the use of these products within operations. Ongoing collaborations and scientific leadership has resulted in 5 peer-reviewed publications and over 30 presentations to the meteorological community, demonstrating SPoRT's continued leadership in the process of transitioning research products and techniques to operations.

Using 12 years of TRMM rainfall data (with orbit boost correction), NASA scientists find that a warmer tropical ocean favors a large increase in occurrence of extreme heavy rain events in a warmer climate (near doubling for every degree increase in tropical sea surface temperature). The increase is coupled to a modest reduction in light to moderate rain, and a slight increase in very light rain over the tropic. This shift in tropical rainfall distribution is similar to that found in previous studies for multi-decadal rainfall trend. The paper demonstrates that TRMM data, when used appropriately, can shed new light regarding how the tropical rainfall systems may respond in a warmer climate (Lau and Wu, 2011). This work together with the authors' previous work has led to a new way of evaluating the veracity of future extreme rainfall projections in IPCC AR5 climate models (Lau et al. 2012, paper in preparation).

Tropical cyclone is a form of extreme weather event, with highly destructive power. Using GPCP and TRMM rainfall data, NASA scientists find that storms are becoming more energetic (wetter) in the North Atlantic, but less energetic (drier) in the North Pacific in the last two decades. These shifts are consistent with long-term changes in sea surface temperature and wind shear over the two ocean basins. This work also provides an alternative to the conventional way of classifying tropical cyclones based on instantaneous winds, *i.e.*, the Saffir-Simpson scale, using rainfall in terms of latent energy per storm (EPS). The EPS classification has the advantage of being universal for all ocean basins, not subject to sampling errors involved in measurement of instantaneous winds. As the length of the PMM rainfall dataset increases, the EPS classification will become more important.

A published article documents a successful attempt by NASA scientists to improve the prediction of a catastrophic set of extreme precipitation events that occurred in Pakistan at the end of July 2010. The forecast improvement comes from the implementation, in the NASA global model and GEOS-5 assimilation system, of additional information derived

from using partially cloudy sky retrievals from the NASA Atmospheric Infrared Sounder (AIRS), an advanced sensor on board the NASA Aqua satellite. The results of these experiments show that the moist flow from the Indian Ocean, and the concentration of moisture in the days preceding the precipitation peak, which are important players in the genesis of the extreme rainfall, are better represented when the cloudy retrieval methodology is adopted. These findings have noteworthy implications in the forecasting ability to predict extreme precipitation events.

FY 2011 Annual Performance Goal	FY 09	FY10	FY11	FY12
2.1.2.1: ES-11-5: Demonstrate planned progress in enabling improved predictive capability for weather and extreme weather events. Progress relative to the objectives in NASA's 2010 Science Plan will be evaluated by external expert review.	Green	Green	Green	Green

Objective 2.1.3: Progress in quantifying, understanding, and predicting changes in Earth's ecosystems and biogeochemical cycles, including the global carbon cycle, land cover, and biodiversity.

Ongoing NASA studies are advancing our understanding of changes in Earth's ecosystems, land cover, and biogeochemical cycles. Satellite observations are being used to quantify these changes and, when used within numerical models, to improve our ability to predict impacts and future changes. Highlights of research conducted in the past year are summarized below.

The discovery of massive phytoplankton (free-floating single-celled photosynthetic organisms at the base of the marine food web) blooms under Arctic sea ice is a major advance in understanding that resulted directly from the Impacts of Climate change on the Eco-Systems and Chemistry of the Arctic Pacific Environment (ICESCAPE) Program. Prior to this field program, estimates of pan-Arctic primary productivity assumed that the growth and biomass of phytoplankton were negligible in waters beneath ice because of insufficient light. However, the 2011 ICESCAPE cruise observed a bloom beneath the 0.8- to 1.3-m-thick first-year sea ice on the Chukchi Sea continental shelf. 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.

The dynamics of Arctic and sub-Arctic vegetation was the topic of several individual research papers and a special issue of *Environmental Research Letters* published in late 2011. Arctic vegetation has been changing in response to changes in climate, and these changes are widespread through the circumpolar North. Understanding the details of these vegetation dynamics spatially and temporally, as well as the mechanisms of change, is crucial to projecting the future of this extensive, heterogeneous, and important biome.

While the Arctic tundra has shown indications of ubiquitous increases in vegetation ('greening'), there are clearly areas that are not greening, and the boreal forest appears to be changing in many places in the opposite direction (i.e., 'browning'). The special issue addressed recent dynamics of Arctic and sub-Arctic vegetation in response to climate change and other disturbances, examined through a variety of techniques including remote sensing, simulation modeling, field observations, and field experiments. Other NASA remote sensing-based results published on changes in Arctic and boreal ecosystems report increases in leaf area and greenness of ~20-60% over the past two decades for shrub and grass tundra expansion in northern Quebec; a net reduction of more than 6,700 km^2 in the surface area of water in lakes across Canada; and a 73% reduction in the strength of the boreal sink in recent decades, estimated through a modeling approach.

In 2012, the first remote-sensing based products from NASA's Carbon Monitoring System (CMS) pilot studies were released for review and further quality assessment. The biomass pilot study's products included a U.S. forest biomass map, state biomass maps for California and Maryland, and local biomass maps for 4 sites in the eastern U.S. The flux pilot study's products included modeled carbon dioxide (CO_2) exchanges between terrestrial ecosystems and the atmosphere and the ocean and the atmosphere using differing NASA models, including both "bottom-up" and "top-down" approaches. CO_2 mixing ratio products, useful for estimating carbon budgets, were also developed. A new CMS Science Team and Science Team Leader were solicited and selected in 2012; the new CMS work will focus on advancing the development of a carbon monitoring system, building upon the lessons learned in the pilot studies and scoping efforts. As per Congressional direction, more than 50% of the Fiscal Year 2012 CMS funding (specifically, 68% of the $10M in the CMS line) is being awarded to external institutions.

In related research, active remote sensing approaches (lidar and radar) similar to those used in the CMS biomass pilot study were employed to create a benchmark map of forest carbon stocks in tropical regions across three continents. This 2011 research paper was followed by one that used those benchmark estimates of forest carbon stocks to then estimate gross carbon emissions between 2000 and 2005, yielding estimates that are 25-50% lower than other recently published estimates. Another recent remote sensing study using ICESat lidar data produced a new global map of forest canopy heights. An overview paper published by NASA-sponsored scientists assessed the role of remote sensing for monitoring carbon stocks and changes. It discusses how satellites and new technologies are revolutionizing the way forest carbon is measured and emphasizes the importance of lidar.

Other research findings focused more generally on the remote sensing of vegetation structure. A special issue of *Remote Sensing of Environment* was completed and published in late 2011. It focused on the three-dimensional (3D) structure of vegetation and requirements for the Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission. While their findings are less relevant to the L-band InSAR now being studied, these papers remain as important documentation of vegetation structure science requirements. A new study demonstrating the use of waveform lidar to map

vertical profiles of leaf area index in tropical forests has raised the possibility of better quantification of 3D habitat structure and new opportunities to understand light transmittance within canopies.

Research on remote sensing to understand species, populations, habitat, and biodiversity yielded significant new results in 2012. In one study NASA researchers compared the efficacies of different remote sensing data sets in mapping migratory bird prevalence across a forested landscape. Multi-sensor fusion involving Landsat, discrete return lidar, waveform lidar, and radar data was able to explain between 54 and 75 percent of the variance for all the birds. Airborne hyperspectral data were used in another study to map Plant Functional Types (PFT) in a region of northern Utah at spatial resolutions from 20 to 60 m. Classification accuracy was dependent on the spatial resolution – important results for future HyspIRI mission plans. In yet another study, imagery from the MODIS sensor enabled the development of a Global Disturbance Index, which mapped hotspots of disturbance for 2005 to 2009 and served as validation for large-scale disturbance patterns across the Pacific Northwest. As a result, climatic-based models correctly predicted current distributions of 15 tree species.

Species abundance in ocean ecosystems was the subject of two new studies. In one, generalized additive models were used to evaluate the power of remotely sensed ocean data along with *in situ* hydrographic and bottom data to explain distributions of 4 species important in the Mid-Atlantic Bight ecosystem that have different vertical habitat preferences. In the other, researchers combined chemotaxonomic analysis with satellite-derived distributions of specific phytoplankton pigments to describe the distributions of particular components of the phytoplankton community in the northeast coast of the United States. The spatial and seasonal variations in phytoplankton community structure generally agreed with observations of abundance estimates of cell counts. While still preliminary, satellite-derived taxa-specific information with proper regional controls holds promise for providing information on phytoplankton abundance to a taxonomic group level, which would greatly improve our understanding of the impacts of human activity and climate change on ecosystems.

The first results from analysis of NASA remote sensing data collected over the 2010 Deepwater Horizon oil spill were published during the past year. An overview paper reported that spill and impact monitoring was aided by extensive airborne and spaceborne passive and active remote sensing. Oil slick thickness and oil-to-water emulsion ratios, key spill response parameters for containment/cleanup, were derived quantitatively for thick (>0.1 mm) slicks from NASA's AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) data using a spectral library approach based on the shape and depth of near infrared spectral absorption features. MODIS (Moderate Resolution Imaging Spectroradiometer) observations, taking advantage of the effects of surface-slick modulation of the sun glint reflection, were used to extrapolate the AVIRIS-based estimates to the total slick. MODIS data proved to be critical for oil spill response decision making due to their frequent temporal coverage, broad spatial coverage, and timely availability. The NASA UAVSAR's (Uninhabited Aerial Vehicle SAR) significantly greater signal-to-noise ratio and finer spatial resolution allowed successful

pattern discrimination of oil slick characteristics and also was useful in identifying shoreline marsh damage. *In situ* burning and smoke plumes were studied with AVIRIS and corroborated with spaceborne CALIPSO (Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation) observations of combustion aerosols. NASA researchers were also able to address concerns about the impacts of the oil spill on the western stock of the Atlantic bluefin tuna. They used a recently developed spawning habitat model that combined historical data on locations of bluefin larvae, environmental data from satellites (sea surface temperature, surface chlorophyll, and surface height), and modeled surface current velocities to assess the impacts of the oil spill. Initial results showed that on a weekly basis, up to 5% of spawning habitat was likely to have been affected by surface oil, with up to 11% potentially affected by oil-contaminated waters.

During the past twelve months, the final project-level synthesis paper and new special journal issues for the NASA contributions to the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) were published. The synthesis paper in *Nature* characterized the Amazon basin as a system in transition due to the combined effects of agricultural expansion and climate variability. Interactions among deforestation, fire, and drought are yielding signs of an impending transition to a disturbance-dominated regime. The special issue of *Biogeochemistry* focused on coupling land and water processes across pristine and impacted systems and reported pronounced impacts of land use changes on hydrologic flowpaths, stream chemistry, and carbon transformations. A Special Feature of the *Proceedings of the National Academy of Sciences* included several LBA papers covering land use, food production, greenhouse gas emissions, and sustainability in the Amazon. Other 2011-2102 papers reported on drought and fire response, deconvolving deforestation and soybean agriculture, and the final results of a selective logging manipulative experiment. The first results of an LBA follow-on study to further assess the carbon balance of the Amazon region (BARCA) were also published. This paper focused on carbon monoxide (CO) and reported strong differences between the wet and dry seasons as well as the important role of biomass burning emissions in the dry season. Comparison of these data with modeled CO emissions confirmed some model capabilities, but also identified important issues to re-assess in high-resolution chemistry-transport models.

In late 2011, NASA-funded scientists published results demonstrating a predictive relationship between sea surface temperature anomalies and annual fire season severity in South America that enables forecasts with lead times of 3-5 months. The empirical model of fire season severity was developed using 2001–2009 fire counts detected by MODIS onboard NASA's Terra satellite along with Oceanic Niño Index (ONI) and Atlantic Multidecadal Oscillation index (AMO) sea surface temperature anomaly time series. In May 2012, these researchers released their first experimental forecast of fire season severity applicable to the Amazon and other regions in South America.

Research to analyze carbon dynamics and the impacts of disturbance in North America continued in 2011-2012, both under the auspices of the interagency North American Carbon Program (NACP) and under related NASA program elements. A major NACP synthesis paper emphasized the importance of integrative analyses employing data from

satellites, flux towers and chambers, long-term process studies, and historical reconstructions and featured an analysis of disturbance severity across North America using a new MODIS Global Disturbance Index (MGDI) for 2005-2009. Researchers working on the North American Forest Dynamics project analyzed forest carbon sinks for the past two decades using Landsat and USDA Forest Service Forest Inventory and Analysis (FIA) data and concluded that forest disturbance and recovery can only account for about one half of the FIA-measured carbon stock change. In another NACP results paper, a national crop carbon budget was balanced to within 0.3-6.1% per year for 2000-2008. In yet another paper, NASA-sponsored researchers used MODIS-derived net primary productivity data to estimate primary bioenergy potential for the U.S. and concluded that current U.S. government expectations for bioenergy production may need to be more realistically constrained.

FY 2011 Annual Performance Goal	FY 09	FY10	FY11	FY12
2.1.3.1: ES-11-7: Demonstrate planned progress in quantifying, understanding, and predicting changes in Earth's ecosystems and biogeochemical cycles, including the global carbon cycle, land cover, and biodiversity. Progress relative to the objectives in NASA's 2010 Science Plan will be evaluated by external expert review.	Green	Green	Green	Green

<u>Objective 2.1.4</u>: Progress in quantifying the key reservoirs and fluxes in the global water cycle and assessing water cycle change and water quality.

The cycling of energy and water has obvious and significant implications for the health and prosperity of society. The availability and quantity of water is vital to life on earth and helps to tie together the Earth's lands, oceans and atmosphere into an integrated physical system.

Over the past year, NASA has continued progress toward improving its description of the water cycle, including the size and movement between its stores. Coincidental use of multiple satellite data sources (e.g. AMSR-E, TRMM, MODIS, etc.), especially those of different but linked variables have led to improvement both in the quantification of the water cycle and the uncertainty estimates of its terms. Two newly provided variables from space, groundwater and total storage, have been enabled from GRACE observations of the changing geoid of the earth which, at monthly time scales, is strongly coupled with the movement of water.

GRACE data's contribution of large area assessment of water movement has been transformed via data assimilation into Land Surface Models (LSMs), which are responsible for tracking the vertical movement of water and energy between the atmosphere and land, as well as contribution to river runoff. This coupling of capabilities led to improvement in 17 out of 18 global river basins, some of which are at finer spatial scales than the GRACE observation footprint (for total water storage). This coupling has also led to improved assessment of changes in groundwater stores in the United States. This information has been blended easily into the work of the US Drought Mitigation

Center as some of their data inputs also come via LSMs. Overall, these developments have been helpful during a period of increasing areal extend and severity of drought in the United States, especially since there has been no accompanying increase in ground based measures of root-zone soil moisture or groundwater.

The earth's water and energy cycles are linked in many ways: when water changes phase, as during precipitation or evaporation, there is an accompanying release or use of energy. Also, clouds and atmospheric water vapor are important regulators of the fluxes of energy in the atmosphere. The NASA Energy and Water cycle Study (NEWS) has compiled the first-ever satellite –based climatologies of both the water and energy cycles. These climatologies are at higher resolutions than typical water and energy cycle budgets, including monthly and continental/oceanic averages. Because of the interaction between these two cycles, improved depiction of one implies added constraints of the other. This gives added veracity to confidence estimates for each cycle. In addition, when combined with NASA's Modern Era Retrospective-Analysis for Research and Applications (MERRA) reanalysis, further study of weather and climate variability is possible, including analysis of the model's capability to reproduce extreme events, such as floods and droughts.

When looking at climate projections, it is important to assess the sensitivity of the system components to climate extremes and to understand the impact that these extremes might have. River basins provide the natural boundaries over which to "index" water resources renewal relevant to most human and natural systems. For example, any substantial change in runoff would have serious societal, environmental and ecological consequences over a basin. NASA investigators looked at sensitivity of 194 major river basins across the globe, as captured with models, to determine their sensitivity to global mean temperature, as a proxy for other potential changes. Results show that the runoff sensitivity implied by the IPCC experiments is relatively stable across emission scenarios and global mean temperature increments, but varies substantially across models with the exception of the high-latitudes and currently arid or semi-arid areas.

The unprecedented snowfall in the Baltimore/Washington region, and greater East coast during the winter of 2009-2010 unveiled important aspects of water cycle dynamics and the value of snowpack remote sensing. Specifically, concerted effort was made to link the remotely sensed falling snow observations to remote sensed snow cover and snow pack observations during those storms. Detailed study revealed the strong influence of the Arctic Oscillation on creating conditions favorable for record snowfall and showing the impacts of snow intensity and liquid water clouds on our ability to detect snow water equivalent and other snowpack properties as they evolve in time. These are both important for future understanding about the forces on the water cycle and our ability to measure it using remote sensing.

Along these lines, work continues on the Soil Moisture Active Passive (SMAP) satellite mission, a concept recommended to NASA by the National Research Council's Committee on Earth Science and Applications from Space (aka the Decadal Survey). SMAP will provide comprehensive global mapping measurements of soil moisture and freeze/thaw state. The first will improve our assessment of water in the surface layer and the root-zone soil. The latter is a critical piece for improving understanding of both the water and carbon cycles. In the past year, the project has generated Algorithm Theoretical Basis Documents that explain the science background and approach to using

the remotely sensed signals that the satellite receives to measure ground quantities. The project is using a computational test-bed to generate synthetic measurements pre-launch in an attempt to uncover potential problems and provide guidance to pre- and post-launch field campaigns that are instrumental at providing refinement and eventual validation of the algorithms. Unprecedented within NASA, the project has also begun to share this data with "early adopters" in the applied sciences arena so that environmental decision makers (and policy setters) can get a jumpstart on using SMAP data soon after launch. This endeavor and in general the efforts of the SMAP project to link with decision makers drew praise in the NRC's interim review report of the original "Decadal Survey".

Multiple NASA endeavors continue to pursue generation and refinement of long term records of water cycle variables. Long term records of precipitation found in the climate prediction Center's Merged Analysis of Precipitation (CMAP) and the Global Precipitation Climatology Project (GPCP) were used to investigate the climate system at decadal scales. The temporal and spatial characteristics of decadal scale variability in the Northern hemisphere cool season (Oct – March) Arctic precipitation were seen in both aforementioned precipitation data sets. This decadal variability is shown to be partly connected to the decadal scale variations in the tropical central Pacific sea surface temperatures that are primarily associated with a decadal modulation of the El Niño–Southern Oscillation (ENSO), i.e., transitions between periods favoring typical eastern Pacific warming events and periods favoring central Pacific warming events.

FY 2011 Annual Performance Goal	FY 09	FY10	FY11	FY12
2.1.4.1: ES-11-9: Demonstrate planned progress in quantifying the key reservoirs and fluxes in the global water cycle and assessing water cycle change and water quality. Progress relative to the objectives in NASA's 2010 Science Plan will be evaluated by external expert review.	Green	Green	Green	Green

Objective 2.1.5: Progress in understanding the roles of ocean, atmosphere, land, and ice in the climate system and improving predictive capability for future evolution.

NASA continues to support research that seeks to better observe our changing planet and understand the role of the oceans, atmosphere, ice, and their interactions in the Earth's climate system. Recent efforts have focused on the collection and interpretation of data acquired from satellites, aircraft, and ground networks; the integration of these data into numerical models of the climate and its components at global and regional scales; and use of models for interpretation and prediction. Over the past year, the observations continue

to show higher than expected surface temperatures and sea level, as well as a decrease in sea ice extent and an increased loss of continental ice, all indicative of a warming climate.

Studies of sea level rise between 1961 and 2008, performed with a combination of radar altimetry, tide gage and other data, reveal a rate of +2.1 mm/yr (+3.4 mm/yr from 1993-2008). The El Niño-Southern Oscillation (ENSO), which is associated with precipitation falling over the continents rather than the oceans, caused a two-year dip in the curve beginning in 2011. Over the last year, the first results from the Aquarius/SAC-D mission, launched on 10 June 2011, began appearing in the scientific literature. Its global sea-surface salinity data provided the first observation of the salinity structure and propagation properties of tropical instability waves in the equatorial Pacific. Satellite sea-surface temperature (SST) data are contributing to our understanding of ocean dynamics and their impact on weather and climate. Recent studies showed that the frequent accurate data from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) yield better estimates of tropical cyclone intensity than other sources of SST data.. Additionally, the observed combined variability of SST with wind data off the coast of Peru revealed the influence of the combined forcing of ocean equatorial Kelvin waves and migratory atmospheric disturbances in the mid-latitudes. Microwave scatterometor, QuikSCAT, data also played a significant role in providing insights into ocean-atmosphere interactions. Used in conjunction with SST data from AMSR-E, shipboard, and other data, QuikSCAT data revealed that the magnitude of the SST seasonal cycle south of the Polar Front in the Drake Passage was doubled north of the front; no other latitude dependence was found in other observed variables or in the derived turbulent heat fluxes. QuikSCAT data were also evaluated with other satellite and reanalysis data and coastal and buoy meteorological observations. This study led to the discovery of one of the dominant summer North Atlantic Oscillation signals in the northern hemisphere, which, together with the air temperature, meridional atmospheric circulation, and cloudiness over the eastern Mediterranean, modulates the Anatolian low.

Satellite data during the past year continued to show a decline in Arctic sea ice cover, both in extent and thickness. The Arctic sea-ice extent dropped to 3.41 million square kilometers, which is well below the previous record of 4.17 million square kilometers observed in 2007. Also the drastic reduction of older perennial sea ice in the Arctic Ocean has resulted in a substantial increase of younger and saltier sea ice with the subsequent release of bromine monoxide and the reduction of atmospheric ozone and mercury. The thinning Arctic ice also appears to allow sunlight to reach the underlying water, catalyzing previously-unobserved phytoplankton blooms; this yielded blooms with growth rates up to 10 times higher than those in adjacent open water. A large-scale survey of snow depth on sea ice was conducted using laser altimeter and ultra-wideband microwave radar data collected by Operation IceBridge. The results were consistent with historical climatology over multi-year ice, but showed larger differences over first-year ice, suggesting that the increasingly seasonal sea ice cover of the Arctic Ocean has led to an overall loss of snow. The collected snow depths were also used to derive sea ice thicknesses, and both measurements were compared to in situ data, with mean differences of 1 cm for the former and 5 cm for the latter. In addition, satellite radar data, collected

through a broad international collaboration with other space agencies, were processed to provide comprehensive views of glacier velocities in both Greenland and Antarctica. Decade-long time series were generated for nearly all of Greenland's outlet glaciers, revealing complex, inter-regional, and intra-regional variability and suggesting that the ice sheet's contribution to sea-level rise may be on the lower end of current predictions. In Antarctica, it was found that ice flow is driven by a complex set of meandering, size-varying, speed-varying, intertwined tributaries, most likely dominated by basal-slip motion. This discovery challenged the traditional view that ice flow is constrained by internal deformation and disconnected from coastal regions. Furthermore, similar radar data, collected over the ice shelves that extend from Antarctica into the ocean, were used to establish a 30-year time series of elevation change. This will further our efforts to understand the relative roles of surface mass balance and subsurface melting in driving the future evolution of both the ice shelves and the glaciers that feed them. Finally, two key projects are working to provide the Intergovernmental Panel on Climate Change (IPCC) with current assessments and future predictions as it begins to compile its Fifth Assessment Report (AR5). NASA and the European Space Agency (ESA) jointly established the Ice-sheet Mass Balance Inter-comparison Exercise (IMBIE) to reconcile published estimates of ice-sheet mass balance obtained from altimetry, gravimetry, and mass-flux techniques. Separately, NASA initiated the Sea-level Response to Ice Sheet Evolution (SeaRISE) project to assess the potential upper bound on ice-sheet contributions to future sea level and its associated uncertainties. Each of the working groups associated with these projects will submit their results to refereed journals so that they may be considered by the IPCC in drafting the AR5.

Several modeling activities have contributed to better understanding the climate system and improving predictive capabilities. The Ice-Sheet System Model (ISSM), a major new ice-sheet model that was recently completed and released, provides a high-resolution, physically-based representation of the cryosphere for climate studies. An adjoint model of sub ice-shelf circulation was also completed and used to demonstrate the importance of Pine Island ice-shelf melt rates to ocean circulation under the shelf. Modeling of atmospheric processes was pushed to a very high resolution on a global scale, which resulted in a global model with sufficient resolution to resolve cloud systems at the 3.5 km scale. The Modern Era Retrospective Analysis for Research and Applications (MERRA), a very successfully reanalysis effort by NASA, was augmented with a modified reanalysis system that featured a significantly improved land surface analysis. Coupling between the land surface and the atmosphere was explored via participation in the GLACE-2 project, which demonstrated the importance of soil moisture information to air temperature forecasts at sub-seasonal timescales. NASA also participated in several prediction activities, including the National Multi Model Ensemble, a multi-agency effort to provide experimental, operational multi-model climate prediction, and the Coupled Model Intercomparison Project (CMIP) version 5, which will be used as the basis for the IPCC Fifth Assessment Report. Modeling activities at NASA stress the use of modern, standard-conforming code to increase model robustness and interoperability. A significant step forward in this area was taken this year with the release of a major new version of the Earth System Modeling Framework (ESMF) software. ESMF was initially funded by NASA, but now has multiagency support.

NASA-supported modeling work this year revealed that regulating substances with short-term climate impacts, such as black carbon and methane, would provide substantial near-term mitigation of anthropogenic forcing of climate, as well as significant health benefits. New understanding of the role of dust and black carbon on snow albedos and melt rates improved global model parameterizations and agreement with observations. In addition, the discovery that the altitude of tropical high clouds increases approximately isothermally when the Tropics warms, an effect which is reproduced in model simulations, led to a better physical understanding of the response of tropical high clouds to tropical mean surface temperature. Furthermore, the causes of Eurasian heat waves in 2003 and 2010 were elucidated by NASA modeling, which demonstrated that such events are an amplification of natural patterns of atmospheric variability that are locked in place by ocean and land surface temperature forcing. Hydrologic coupling between ocean and land was also examined in the MERRA reanalysis and was shown to be in good agreement with observations. However, it was also shown that reanalyses that assimilate moisture from satellite observations produce large perturbations due to changes in the observing system, complicating the use of these data sets for trend analyses.

FY 2011 Annual Performance Goal	FY 09	FY10	FY11	FY12
2.1.5.1: ES-11-11: Demonstrate planned progress in understanding the roles of ocean, atmosphere, land, and ice in the climate system and improving predictive capability for future evolution. Progress relative to the objectives in NASA's 2010 Science Plan will be evaluated by external expert review.	Green	Green	Green	Green

Objective 2.1.6: Progress in characterizing the dynamics of Earth's surface and interior and forming the scientific basis for the assessment and mitigation of natural hazards and response to rare and extreme events.

NASA's Earth Surface and Interior Focus Area (ESI) is partitioned into three principal program elements supported by programs across the Earth Science Division. The program elements are (1) the Space Geodesy Program, (2) the Natural Hazards Program, and (3) the Earth Interior Program. FY2012 has seen very significant progress in each of these interrelated programs toward the objectives of 2.1.6 via the development of space geodetic measurement techniques, geodetic remote sensing and geopotential field measurements and the associated modeling and analysis. ESI is guided by the SESWG program plan (http://solidearth.jpl.nasa.gov/seswg.html) in developing an understanding of the transport of mass within the Earth System in response to tectonic, climatic and anthropogenic forces, and to better understand, mitigate, and respond to natural hazards such as earthquakes, volcanic eruptions, tsunamis, landslides, and floods.

1. ***The Space Geodesy Program Element:***

Space Geodesy Project: NASA's Earth Surface and Interior Focus Area (ESI) has prioritized strengthening of the **global geodetic network** infrastructure in response to the recommendations of National Research Council's report *"Precise Geodetic Infrastructure: National Requirements for a Shared Resource"* (2010) (http://www.nap.edu/catalog.php?record_id=12954). NASA/ESD is funding the Space Geodesy Project (SGP) (http://space-geodesy.nasa.gov/) to develop the prototype core geodetic observatory to replace an aging global network. The prototype geodetic observatory will be completed by August 2013 while work will continue on the development of analysis software. Progress to date includes the day and night tracking of GNSS satellites by the automated NGSLR instrument, the end to end acquisition and analysis of quasar signals using broadband (S-K Band) real time acquisition on newly implemented VLBI2010 architecture (http://space-geodesy.nasa.gov/news/VLBI_progress_jan2012.html). NASA/ESD with the support of the NASA administrator and HEOMD/SCaN is leading a consortium of US agencies recommending the placement of SLR retroreflectors on the GPS III satellites.

TriG: NASA/JPL is developing a new GNSS spaceborne receiver, the TriG, to replace the very successful BlackJack GPS receiver (http://authors.library.caltech.edu/21729/ and www.irowg.org/docs/Presentation/meehan.pdf) . The first engineering model and acquisition software with be delivered in March 2013. The receiver will provide the needed positioning and timing capability required for the Decadal Survey missions of the next decade as well as GNSS remote sensing techniques of the occultation and reflection sounding. The US Air Force has procured 8 TriG receivers for the first 6 COSMIC II low inclination orbit satellites (https://www.fbo.gov/index?s=opportunity&mode=form&id=4dd0af785848a4da9ed07a0c663e4e32&tab=core&_cview=1). The selection of CyGNSS as an EV-2 mission (http://www.nasa.gov/home/hqnews/2012/jun/HQ_12-203_Earth_Venture_Space_System_CyGNSS.html) is a product of that investment. The techniques and capabilities of the CyGNSS mission have been developed in part through the support of ESI research and engineering grants and RTOPs.

2. **The Natural Hazards Program Element:**

Real Time GNSS: NASA achieved significant success in demonstrating the capability and potential of real time GNSS ground networks in 2012, in particular the Great Alert program for the real time estimation of earthquake fault motions and tsunami prediction. NASA-funded grants advanced the calculation of real time fault motions such as the demonstration that if the Japanese GEONET GPS data were available in real time, an accurate estimate of the magnitude of the Earthquake would have been available within 2 minutes of the rupture- nearly 12 minutes prior to the first inundation of the tsunami and about 18 minutes prior to the fastest seismic techniques. Furthermore, these real time data could have provided both predictions and observations of the devastating Tohoku tsunamis using GPS-based crustal motion estimate followed by confirmation and tracking via the induced ionospheric gravity waves.

NASA, NSF and several universities have joined in support of the Real-time Earthquake Analysis for Disaster Mitigation (READI) Network of about 500 GNSS receivers in the US West. READI information is available at the GPS Explorer site

http://sopac.ucsd.edu/projects/realtime/READI/index.html. GDGPS (http://www.gdgps.net/system-desc/index.html) 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.

Modeling and Analysis: ESI strongly supports modeling and analysis efforts that utilize geodetic, geodetic imaging, and geopotential field measurement strategies. Last year we reported that NASA funded researchers had identified ULF signals associated with stress changes and earthquakes. In this report, an earthquake probability analysis that utilizes seismicity patterns by Rundle et al was evaluated as a top performer in the Regional Earthquake Likelihood Models (RELM) analysis conducted by the Southern California Earthquake Center. Finally, QuakeSim, a software development effort, funded by NASA's Earth Science Technology Office and the ESI Natural Hazards Program Element has been awarded NASA's Software of the Year Award for 2012. QuakeSim includes software such as Virtual California, a model of the California fault system, and GeoFest, a finite element stress-strain modeling routine.

Geodetic Imaging- Synthetic Aperture Radar (SAR):

Suborbital Radar: The airborne UAVSAR radar and the Ka-Band GLISTEN-A are flown on a Gulfstream-III and are being integrated aboard the Global Hawk UAV. The Global Hawk instrumentation is to be used for the acquisition of high-resolution topography in remote areas. The P-band AirMOSS is also being developed for use on a second G-III made available in March 2011 under the Earth Venture-1 program, with engineering flight tests scheduled to begin in September 2012. GLISTEN-A on the G-III demonstrated the SweepSAR technique planned for use by DESDynI-Radar in July 2011. UAVSAR has served 25 principal investigators. 2011-2012 deployments and objectives include: (1) volcanic deformation studies of Cascades, Aleutian Islands, Hawaii and Central America, (2) deformation associated with plate boundaries in California along the San Andreas, Hayward and associated faults and fault systems in Hispaniola, (3) surface deformation associated with Gulf Coast subsidence, (4) surface deformation associated with levee conditions in the Sacramento and Mississippi deltas, (5) environmental impacts of the Gulf oil spill, (6) SMAP soil moisture cal/val campaign in Winnipeg, Canada, and (7) temperate glacier study in Iceland. Having completed its fourth year of science data acquisitions, results are beginning to emerge in the published journal literature with 9 published, 3 in press, 2 in review, and more than 5 in preparation. UAVSAR data revealed the unexpected complexity of faulting during the El Mayor-Cucapah earthquake and identified previously unknown faults (Liefert, 2011). UAVSAR demonstrated the utility of a high-resolution, polarimetric, L-band SAR to provide information on oil containment booms both in and out of water that is relevant to disaster response/management (Jones, 2011), as well as the detection of levee break in the Sacramento Delta.

3. **The Earth Interior Program Element:**

NASA utilizes both geopotential fields and geodetic observations to study the Earth's interior. This program element seeks to focus more on whole Earth challenges including the geodynamo, Earth Rotation, Glacial Isostatic adjustment, tectonics, etc. NASA ESI

provided support to the SWARM mission for the development and application of comprehensive field models. The three-satellite SWARM mission is scheduled for launch by ESA in late 2012. A small number of NASA researchers have been funded to participate in the SWARM science team. ESI has also funded the development of a new advanced self-calibrating miniature helium magnetometer to be delivered in February 2013. The program will seek to demonstrate the instrument on airborne and microsatellite platforms and to achieve the launch of a small satellite constellation as called for in the SESWG program plan. NASA geomagnetic field research contributes to field models for navigation, core dynamics, crustal evolution, and natural hazards.

FY 2011 Annual Performance Goal	FY 09	FY10	FY11	FY12
2.1.6.1: ES-11-15: Demonstrate planned progress in characterizing the dynamics of Earth's surface and interior and forming the scientific basis for the assessment and mitigation of natural hazards and response to rare and extreme events. Progress relative to the objectives in NASA's 2010 Science Plan will be evaluated by external expert review.	Green	Green	Green	Green