EARTH SCIENCE DIVISION

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

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

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<u>Annual Performance Indicator ES-17-1:</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.

NASA's Atmospheric Composition Focus Area (ACFA) continues to provide quantitative global observations from space, augmented by suborbital and ground-based measurements of atmospheric aerosols and greenhouse and reactive gases, enabling the national and international scientific community to improve our understanding of their impacts on climate and air quality. In particular, ACFA helped to gain insights into changes in the Earth's radiation balance, our prognostic capability for the recovery of stratospheric ozone and its impacts on surface ultraviolet radiation, and the evolution of greenhouse gases and their impacts on climate, as well as the evolution of tropospheric ozone and aerosols and their impacts on climate and air quality. The ACFA research utilizes and coordinates advances in observations, data assimilation, and modeling to better understand the Earth as a system. Selected research results and other accomplishments of the 2017 fiscal year are highlighted below.

Aerosol and cloud radiative effects research

Aerosols have a potentially large effect on climate, particularly through their interactions with clouds, but the magnitude of this effect is highly uncertain. The processes and radiative effects in the coupled system of clouds and aerosols are some of the most challenging problems we face in the quest for better understanding of recently observed global changes, as well as being able to better predict the future climate.

- **Volcanic aerosols affect cloud properties**
  Nature published a case study by Malavelle et al. (2017) using MODIS aerosol and cloud data showing that a massive volcanic eruption in Iceland reduced the size of liquid cloud droplets—consistent with expectations—but had no discernible effect on other cloud properties. The reduction in droplet size led to cloud brightening and global-mean radiative forcing of around minus 0.2 watts per square meter for September to October 2014. Changes in cloud amount or cloud liquid water path, however, were undetectable, indicating that these indirect effects, and cloud systems in general, are well buffered against aerosol changes. These results may represent an important constraint on climate models.

- **Atlantic marine stratocumulus clouds cool the planet due to Saharan dust**
  A study by Amiri-Farahani et al. (2017) suggests that Saharan dust modifies Atlantic marine stratocumulus clouds such that they cool the planet. They find a strong seasonal variation, with the aerosol–cloud radiative effect switching from significantly negative during the boreal summer to weakly positive during boreal winter. This study used observational data for the time period between 2004 and 2012, mainly from CALIPSO and from the Monitoring Atmospheric Composition

and Climate (MACC) reanalysis dataset. The semi-direct radiative effect is estimated with two different methods, leading to coherent results.

- **Brown carbon contributions to warming at the tropopause**
  Carbonaceous aerosols affect the global radiative balance by absorbing and scattering radiation, which leads to warming or cooling of the atmosphere, respectively. A portion of the organic aerosol known as brown carbon also absorbs light. The climate sensitivity to absorbing aerosols rapidly increases with altitude, but brown carbon measurements are limited in the upper troposphere. Zhang et al. (2017b), using aircraft observations from the SEAC4RS campaign of vertical aerosol distributions over the continental United States in May and June 2013, show that light-absorbing brown carbon is prevalent in the troposphere. The results show that brown carbon absorbs more short-wavelength radiation than black carbon at altitudes between 5 and 12 km. It was observed that brown carbon is transported to these altitudes by deep convection, that in-cloud heterogeneous processing may produce brown carbon, and they suggest that brown carbon accounts for about 24% of the combined black and brown carbon warming effect at the tropopause. They conclude that high-altitude brown carbon from biomass burning is an under-appreciated component of climate forcing.

- **Drylands more affected by climate change**
  Nature published an article by Huang et al. (2017) showing that drylands are affected by climate change to a greater degree, with an increase of mean surface temperature of more than 40% above the global warming limit of 2°C set by the Paris Agreement. They used MODIS aerosol and cloud observations, as well as other data, as input to climate model simulations to estimate these radiative effects.

- **Reduced uncertainty in Arctic net aerosol indirect effects**
  Aerosol indirect effects have uncertain, but potentially large, impacts on the Arctic energy budget. Zamora et al. (2017) have reduced uncertainty in estimates of current-day Arctic net aerosol indirect effects. They achieved this by better constraining various characteristics of optically thin, liquid-containing clouds in clean, average and aerosol-impacted conditions using a combination of CALIPSO and CloudSat data and model output. The work provides a foundation for how future observational studies can evaluate model estimates of the aerosol indirect effect.

- **Accelerated summertime warming in the Southeast U.S. due to reductions in aerosols?**
  During the twentieth century, the southeast United States cooled, in direct contrast with widespread warming. In a study by Tosca et al. (2017), observations by the MISR and CALIPSO satellite instruments of aerosol optical depth and aerosol vertical profiles are combined with a radiative transfer model and surface temperature observations to diagnose how major reductions in summertime aerosol burden since 2001 could have impacted surface temperatures in the southeast US. A significant improvement in air quality likely contributed to the elimination of the warming hole and acceleration of the positive temperature trend observed in recent years. These reductions coincide with an EPA rule that was implemented between 2006 and 2010 that revised the fine particulate matter standard downward. Similar to the southeast US, other regions of the globe may experience masking of long-term warming due to greenhouse gases, especially those with particularly poor air quality.

- **Science summary from ten years of joint observations by CloudSat and CALIPSO**
  Stephens et al. (2017) show how the more than 10 years of observations jointly collected by CloudSat and CALIPSO satellites clearly demonstrate the fundamental importance of the vertical structure of clouds and aerosol particles. These satellites increased the understanding of the influences of larger scale atmospheric circulation on aerosol distributions, the hydrological cycle, cloud-scale physics, and the formation of major storm systems.
- **Overview and science summary of the DRAGON project**
  During the past 24 years, the AErosol RObotic NETwork (AERONET) program has provided ground-based remote sensing characterization of aerosol optical and physical properties from an increasingly extensive geographic distribution that includes all continents and many island sites. The measurements and retrievals from AERONET have addressed satellite and model validation needs very well. An effort to address remaining challenges with the comparison of in situ surface with satellite aerosol observations resulted in a number of field campaign networks called Distributed Regional Aerosol Gridded Observation Networks (DRAGON). A paper by Holben at al. (2017) describes the networks and resulting analysis of local to mesoscale variability of aerosol properties.

Tropospheric and air quality research

Air pollution from ozone and other trace gases in the boundary layer is affecting health and welfare significantly. And worse, fine particulate matter ($PM_{2.5}$) is known to be associated with adverse respiratory and cardiovascular health impacts. Air quality data are routinely collected at outdoor monitors across the U.S. and in some major cities around the globe. Such data are temporally continuous, but lack spatial coverage. Especially in urban areas, air quality tends to be highly variable in time and space. To address this data gap, NASA will provide new complementary observations of the spatial distribution of trace gas and aerosol abundance with the upcoming MAIA and TEMPO satellite instruments. This combination of space- and ground-based observations with chemical transport models is expected to enhance the capabilities and accuracies of urban air quality data used in forecasts and health studies.

- **Observed reduction of particulate air pollution due to closing of coal-fired power plants**
  With the ongoing controversy about closing coal-fired power plants across the United States, there is interest in the potential impact on regional $PM_{2.5}$ concentrations. A study by Russell et al. (2017) explored the impacts of closing three coal-fired power plants in southwestern Pennsylvania to investigate regional air quality from January 2011 through December 2014. They used MODIS and EPA $PM_{2.5}$ ground stations in order to check the performance of a series of models. Using these observations, this study found that the models were correctly predicting the downward trend in aerosol loading following each power plant shutdown.
- **Has China been exporting less particulate air pollution over the past ten years?**
  Particulate matter pollution from China is transported eastward to Korea and Japan and has been suggested to influence surface air quality on the West Coast of the

United States. Using MISR, MODIS, and AERONET data, a study by Zhang et al. (2017a) found that aerosol optical depth, as an indicator of particulate pollution, had increased until 2007 in the main exit regions of China's coast. Since then, there has been a 10–20% decrease in aerosol optical depth. Reductions were observed in spring, summer, and fall seasons. No reduction was observed for the winter season.

- **Increase in dust storms in the U.S.?**
  A new statistical model suggests that climate change will amplify dust activity in parts of the U.S. in the latter half of the 21st century, which may lead to increased frequency of large dust storms that have far-reaching impacts on public health and infrastructure. This model, detailed by Pu et al. (2017), eliminates some of the uncertainty found in previous dust activity models by using present-day satellite data such as dust optical depth, leafy green coverage over land, and other factors.

- **Change in tropospheric ozone due to shifted emissions towards low latitudes**
  Ozone is an important air pollutant at the surface, and the third most important anthropogenic greenhouse gas in the troposphere. Since 1980, anthropogenic emissions of ozone precursors have shifted from developed to developing regions. Emissions have therefore been redistributed equator-ward, where they are expected to have a stronger effect on the tropospheric ozone burden due to greater convection, reaction rates, and NO_x sensitivity. NASA's GEOS-5 global chemical transport model was used by Zhang et al. (2016), who estimated that the increase in ozone burden due to the spatial distribution change slightly exceeds the combined influences of the increased emission magnitude and global methane, one of the precursors of ozone. The model results were found to be consistent with observations from NASA's SHADOZ ozonesondes, OMI, and MLS satellite instruments. This *Nature* publication also suggests that increasing emissions in Southeast, East and South Asia may be most important for the ozone change. The spatial distribution of emissions dominates global tropospheric ozone, suggesting that the future ozone burden will be determined mainly by emissions from low latitudes.

- **NO_x emission controls ozone and formaldehyde air quality**
  Formaldehyde (CH_2O) is a dominant carcinogen in outdoor air and a precursor for tropospheric ozone. Zhu et al. (2017) used OMI satellite data, validated with aircraft in-situ data, and the GEOS-Chem chemical transport model to map surface air formaldehyde concentrations across the contiguous U.S. Based on this novel dataset, they estimate that up to 6,600-12,500 people in the U.S. will develop cancer over their lifetimes by exposure to outdoor formaldehyde. Further, they find that formaldehyde levels would decrease by 20-30% in the absence of U.S. anthropogenic NO_x emissions. Thus, NO_x emission controls to improve ozone air quality have a significant co-benefit in reducing formaldehyde-related cancer risks.

- **TES Megacity Measurements highlighted in the journal *Science***
  A new dataset from Aura TES measurements provides insights into spatial and temporal variations of trace gases including ammonia, formic acid, methanol, and ozone over 19 megacities since 2013. Using those data, Cady-Pereira et al. (2017) show that while Mexico City is known for severe pollution events, the levels of pollution in Lagos are much higher and more persistent. Based on this study, the journal *Science* requested data from all 19 sites and published an article (https://doi.org/10.1126/science.aal0942) on the frequency of high ozone and ammonia

days around the world. The Science article concluded that South Asia, in particular, has a large proportion of both high-ozone and high-ammonia days, indicating a significant health risk for the urban population.

- **Assimilation of multiple global satellite datasets reduces uncertainties in observations of surface trace gas concentrations**
  Miyazaki et al. (2017) found that, despite large trends observed for individual regions, the global total emissions of nitrogen oxides, ozone, and carbon-monoxide were almost constant between 2005 and 2014. They assimilated multiple satellite trace gas datasets (NO_2 columns from OMI, GOME-2 and SCIAMACHY, O_3 profiles from TES, CO profiles from MOPITT, and O_3 and HNO_3 profiles from MLS) to reduce uncertainties in global surface concentrations.

- **MAIA and TEMPO: upcoming instruments to observe air quality from space**
  Ground breaking improvements to the observation and ultimately to the understanding of sources and effects of air quality due to particulate matter and trace gases can be expected from the upcoming NASA's Earth Venture Instruments MAIA and TEMPO missions. The missions were recently highlighted by Liu and Diner (2017) and Zoogman et al. (2017).

Upper atmospheric and ozone depletion research

Stratospheric composition remains an area of interest 32 years after the discovery of the Antarctic ozone hole and 30 years after the adoption of the Montreal Protocol to limit substances that destroy the ozone layer. NASA has an ongoing mandate to continue research in understanding changes in ozone and ozone depleting substances through the Clean Air Act.

- **Atmospheric abundance and global emissions of perfluorocarbons since 1800**
  Perfluorocarbons (PFCs) are very potent and long-lived greenhouse gases in the atmosphere, released predominantly during aluminum production and semiconductor manufacture. Many had been proposed as replacements for ozone depleting substances as well. They have been targeted for emission controls under the United Nations Framework Convention on Climate Change (UNFCCC). Trudinger et al. (2016) published the first continuous record of the abundance and emissions of three PFCs (CF_4, C_2F_6 and C_3F_8) from 1800 to 2014. The histories were derived from atmospheric measurements made at stations in the NASA-sponsored Advanced Global Atmospheric Gases Experiment (AGAGE) global network, archived air samples, and air extracted from polar firn or ice in both hemispheres. Emissions increased rapidly from around 1960, to peak in 1980 (CF_4) or early-to-mid-2000s (C_2F_6 and C_3F_8). Significant mitigation efforts by both the aluminum and semiconductor industries have led to strong decreases in emissions, despite the continued increase in global aluminum production. The decrease in emissions appears to have slowed and possibly stopped in recent years. Continued effort from all PFC-generating industries is urgently needed to reduce the emissions of these potent greenhouse gases, which, once emitted, will stay in the atmosphere permanently (on human timescales) and contribute to radiative forcing.

- **El Niño-related Indonesian peat fires enhanced upper tropospheric CO**
  Field et al. (2016) presented a broad multi-instrument view of the impact on upper

tropospheric/stratospheric composition of the 2015 El Niño-enhanced Indonesian peat fires. This event represents the largest enhancement in upper tropospheric carbon monoxide seen in the 12-year MLS record to date, and demonstrates a key coupling between climate variability and the stratosphere.

- **Characterization of the Asian Summer Monsoon using MLS**
  The Asian Summer Monsoon anticyclone region is a significant contributor to transport of trace gases to the stratosphere. However, it has been only sparsely sampled by in situ sensors. Santee et al. (2017) has used the MLS record to provide a unique characterization of the decadal (2005–2014) composition of this region throughout its annual life cycle. Inside the mature anticyclone, they found that all species exhibit substantial changes, not only from their pre-monsoon distributions in this region, but also from their summertime distributions in the rest of the hemisphere. Different tracers exhibit dissimilar seasonal evolution, and the exact location and timing of their extreme values vary.

- **New possible explanation for the recent methane growth?**
  Methane is the second strongest anthropogenic influenced greenhouse gas and its atmospheric burden has more than doubled since 1850. Methane concentrations stabilized in the early 2000s and began increasing again in 2007. Neither the stabilization nor the recent growth are well understood. Two related papers were published simultaneously on this topic. Rigby et al. (2017) investigated a possible cause for these transient changes in CH_4 over the past two decades, a rise and fall in the concentration of the substance that destroys methane in the atmosphere, the hydroxyl radical (OH). Rigby et al. (2017) used data from the AGAGE program that has been monitoring trends in methyl chloroform for nearly 40 years because of its role in depleting stratospheric ozone. Methyl chloroform is now banned under the Montreal Protocol for the Protection of the Stratospheric Ozone Layer and its concentration has dropped very rapidly since production and use of it has been reported to have ceased. Such a scenario would suggest that methane emissions may not have increased suddenly in 2007, but rather, have risen more gradually over the last few decades. This study also provides strong evidence that emissions of the globally banned methyl chloroform are still continuing. A similar study on the recent methane growth by Turner et al. (2017) concludes that the current surface observing system does not allow unambiguous attribution of the decadal trends in methane without robust constraints on OH variability, which currently rely purely on methyl chloroform data and its uncertain emissions estimates. Turner et al. (2017) suggests that other independent proxies for OH with higher spatially resolved constraints are needed to better constrain changes in CH_4. Future work could also focus on obtaining higher spatially resolved constraints where the methane-to-ethane ratios and isotopic signatures of the sources are better constrained. This would also allow the use of more gradient information as could be discerned from satellite observations.

Airborne activities

Programmatic and Earth Venture class suborbital missions continued to be a very important contribution of ACFA to supplement current and prepare for future space-borne missions. These missions also enable the investigation of specific research

questions with higher accuracy and resolution than usually possible from space. A few examples are highlighted here.

- **ObseRvations of Aerosols above CLouds and their intEractionS (ORACLES)**
  Aerosol and clouds form complex systems, especially if they interact with each other in diverse ways. For example, we already know that aerosols have the ability to enhance or inhibit the formation of clouds. This can be a strong driver to our planet's energy budget because clouds over vast regions of dark ocean can determine whether the solar radiation is absorbed by the ocean, or if it is sent back to space. We thus need a better understanding of where, when, how often, and how much aerosols are changing clouds in the current and future climates. The subtropical Atlantic is much like a laboratory to study those processes because about one third of the Earth's biomass burning aerosol particles are produced in the southern part of the African continent. Most of them are ultimately blown over the Atlantic, where they can act as climate regulators. The ORACLES Earth Venture Suborbital mission deployed NASA's ER-2 and P-3 in August-September 2016 (Zuidema et al. 2016) with 18 in-situ sampling and remote sensing instruments in total. Early, unpublished results show, for example, that the cloud droplet number is increased significantly if an aerosol plume is mixing with an existing cloud.
  More information: https://espo.nasa.gov/ORACLES/content/ORACLES

- **Pacific Oxidants, Sulfur, Ice, Dehydration, and Convection (POSIDON) Experiment.**
  The NASA Pacific Oxidants, Sulfur, Ice, Dehydration, and Convection (POSIDON) Experiment was a focused airborne science mission to study the OH and sulfur chemistry, cirrus clouds, and dehydration in the tropical upper troposphere and lower stratosphere over the western Pacific. Flights were conducted from Guam during autumn 2016 using the NASA WB-57F aircraft with state-of-the-art instrumentation. The experiment provided measurements that should enable the community to better evaluate a hypothesis of an O_3/OH minimum in the upper troposphere and its possible impact on very short-lived species. In addition, the mission investigated the transport and chemistry of sulfur species to assess the validity of global chemistry transport model projections of anthropogenic sulfur impacts, and obtained measurements of the microphysical properties and water vapor concentration in anvil cirrus detrained from deep convection, as well as thin cirrus near the tropopause that regulate the abundance of water vapor entering the stratosphere.
  More information: https://espo.nasa.gov/posidon

- **Atmospheric Tomography (ATom) capturing global chemical heterogeneity**
  To understand global atmospheric chemistry is to understand the mix of chemicals in the atmosphere and where they come from. Knowledge of the photochemical evolution in each air parcel is needed to understand the overall impact of the mix of chemicals and to interpret human impact on past changes and predict future ones. Moving toward this goal is NASA's ATom aircraft mission (2015–2020). It has completed the summer and winter data collection flying NASA's DC-8 from near the North towards the South pole along the Pacific Ocean and back towards the North pole along the Atlantic Ocean. It is instrumented to make in situ profile measurements of the most important reactive chemical species that control the loss of methane and the production and loss of tropospheric ozone. The resulting climatology should

represent the chemical heterogeneity of the atmosphere, including the covariance of key reactive species. A study by Prather at al. (2017) is comparing six global chemistry–climate models computing air parcel reactivity. The distinctively different model outputs underline the importance of the measurements currently being collected by ATom.
More information: https://espo.nasa.gov/atom

- **Challenges of observing near-surface constituents from geostationary orbit**
The vertical distributions of trace species provide inherent challenges in extracting near-surface measurements (and thus, relevant measurements for human exposure) from the total atmospheric columns measured by satellites. The NASA Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) field campaign was designed to enable exploration of relationships between column measurements of trace species relevant to air quality at high spatial and temporal resolution. Schroeder et al. (2017) observed a modest correlation between ozone (O_3) and formaldehyde (CH_2O) column densities. Further analysis revealed regional variability in the O_3-CH_2O relationship, with Maryland having a strong relationship when data were viewed temporally and Houston having a strong relationship when data were viewed spatially. These differences in regional behavior are attributed to differences in volatile organic compound emissions. Results of this work provide insights into the potential utility of future geostationary satellites to fill in gaps in surface monitoring networks and understand the true spatial extent of air pollution events.
More information: https://discover-aq.larc.nasa.gov/

Orbiting Carbon Observatory-2 results at the end of the prime mission

The Orbiting Carbon Observatory-2 (OCO-2) instrument has collected almost 1 million soundings globally each day since September 2014. It provides a unique dataset able to resolve local and regional sources and sinks, which define global trends of carbon dioxide. OCO-2 finished its prime mission in October 2016 and is now in its first extended mission. A summary of major scientific results and accomplishments will be published in a special collection of several papers in the journal *Science* in late September 2017.

- **Tropical forests as main source of the record increase in CO_2 emissions during the strong 2015-2016 El Niño event**
Data from Mauna Loa Observatory and OCO-2 show that the 2015-2016 El Niño event coincides with the largest annual increase in carbon dioxide (about 3 ppm) since measurements began in the 1950s, even though human emissions were roughly the same as in the preceding year. The work by Liu et al. (2017) shows, using OCO-2 data, that tropical continents were the primary source of that record increase of carbon dioxide, with about 2.5 gigatons higher carbon emissions as compared to 2011, which is considered a normal year. In the 2015-2016 El Niño period, tropical South America, including the Amazon rainforest, was the driest it's been in the last 30 years. Trees went dormant or died, reducing photosynthesis and leaving more carbon in the atmosphere. African rainforests endured hotter-than-normal temperatures. Decomposition of dead trees increased, releasing more carbon to the atmosphere. In

Southeast Asia, drought increased the size and duration of peat and forest fires, releasing more carbon to the atmosphere.

- **CO_2 changes over the Pacific during the strong 2015-2016 El Niño event**
  Chatterjee at al. (2017) performed a detailed look at the total column atmospheric CO_2 measurements from the OCO-2 instrument using observations over the eastern equatorial Pacific. They show a significant reduction of CO_2 due to reduced outgassing from the ocean at the onset of the 2015-2016 El Niño event. This was followed by an increase in CO_2 due to enhanced respiration and biomass burning in South America. They found those regional anomalies ranging from minus 1 ppmv during March through June to plus 1 ppmv of CO_2 during September through spring of 2016 with respect to neutral conditions (approximately 400 ppmv).

- **Local sources and sinks of CO_2 observed by OCO-2**
  Using high spatial resolution OCO-2 images, Schwandner et al. (2017) investigated localized sources and sinks of CO_2 associated with urban centers and volcanoes. On a single orbit, OCO-2 measurements enabled the differentiation of local sources on the order of about 6 ppmv over Los Angeles, California. Overall, they showed differences on the order of 1 ppmv can be quantified with OCO-2.

In addition to the special collection in *Science*, the OCO-2 dataset was also used as a primary tool in many more publications. As an example:

- **Anthropogenic emissions of carbon dioxide directly observed with OCO-2**
  Hakkarainen et al. (2017) shows, for the first time, direct observations of anthropogenic emissions of carbon dioxide from fossil fuel combustion over the eastern U.S., central Europe, and East Asia using OCO-2 data. The authors achieved this by deseasonalizing and detrending the OCO-2 observations to derive CO_2 anomalies. A cluster analysis confirmed the expected spatial correlation between CO_2 and NO_2 in the case of fossil fuel combustions.

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FY2017 Annual Performance Indicator	FY 14	FY15	FY16	FY17
ES-17-1: Demonstrate planned progress in advancing the understanding of changes in Earth's radiation balance, air quality, and the ozone layer that result from changes in atmospheric composition. Progress relative to the objectives in NASA's 2014 Science Plan will be evaluated by external expert review.	Green	Green	Green	Green

Annual Performance Indicator ES-17-3: Demonstrate planned progress in improving the capability to predict weather and extreme weather events.

NASA continues a busy year of research and development with many activities and accomplishments in the Weather Focus Area (WFA; https://science.nasa.gov/earth-science/programs/research-analysis/earth-weather/). Most of the research and development in the WFA continues to be in precipitation science while NASA slowly evolves the focus as precipitation science matures. WFA uses our existing fleet of satellites to take observations of weather systems, produce carefully calibrated data products for scientific interrogations and demonstration with operational decision makers, develop new observation platforms and instruments to expand the observations, perform field campaigns to understand the weather producing processes, study the behavior of weather systems using integrated modeling and data assimilation systems, and organize conferences and workshops to assess our current understanding and to plan for future research and development activities.

Precipitation Science

For almost 30 years, NASA has put a tremendous amount of resources and energy into precipitation science. The Tropical Rainfall Measuring Mission (TRMM) was launched in November 1997 and stopped science operations and data collection in April 2015. However, the extensive 17.5-year data record has continued to provide insights into tropical storm structure and intensification as its products have been transitioned to the Global Precipitation Measurement (GPM) mission products. More than 2800 peer-reviewed publications (based on a search on 'TRMM' by topic or publication title on Web of Science) have resulted from TRMM. In FY2017, NASA finalized and implemented Version 8 algorithms for TRMM, including improved geolocation, calibration, and emissive antenna correction. Version 8 of TRMM is consistent with Version 5 of the GPM algorithms, allowing for creation of a long-term data record combining TRMM and GPM. NASA plans to reprocess the entire 17.5-years TRMM record in FY2018.

The Global Precipitation Measurement (GPM) Core Observatory (GPM-CO) spacecraft launched February 27, 2014 in a partnership between NASA and the Japan Aerospace Exploration Agency (JAXA). The GPM-CO is a key part of the GPM mission (Skofronick-Jackson et al., 2017), which is defined to encompass multi-satellite unified precipitation estimates. As such, the GPM-CO serves as the calibration reference standard for unifying the data from a constellation of approximately 10 partner satellites to provide the GPM mission's next-generation, merged precipitation estimates globally and with high temporal (0.5 hours) and spatial (10 km) resolutions released to the public in near real time.

In the precipitation science area, GPM has taken the main stage and become the main source of precipitation data. A long heritage of highly accurate precipitation retrievals

from spaceborne active and passive instrumentation has been provided by TRMM; however, the instruments on GPM have new capabilities. Thus, much effort has been expended in developing GPM retrieval algorithms for the Dual-frequency Precipitation radar (DPR), GMI, combined DPR+GMI, and merged satellite estimates. Version 5 of GPM Core Observatory Products were released May 2017 and Version 4 of GPM's Constellation merged products (called IMERG) reprocessing began in March 2017 (http://pps.gsfc.nasa.gov). These updated algorithms incorporated DPR's improved calibration, an observational database for GMI, and improvements for light rain, falling snow, and non-spherical particles. Some of the publications related to algorithm development work include: for DPR (Mega and Shige, 2016; Le et al., 2016), for combined DPR+GMI (Grecu et al., 2016; Olson et al., 2016; Kuo et al., 2016; Munchak et al., 2016), for GMI (Turk et al., 2016). Algorithm development work for GPM Version 5 includes careful calibration of TRMM for consistency with GPM so that when TRMM data are reprocessed with IMERG a long record of precipitation from 1998 to present will be available (expected release in Spring 2018), (e.g., Berg et al. 2016). GPM also verified Level 1 Mission Requirements as presented at GPM's successful End of Prime Mission Review in June 2017.

Data from the Global Precipitation Measurement (GPM) mission have produced several scientific accomplishments in the past year. An analysis of GPM data shows an improved representation of monsoon precipitation and its interaction with atmospheric dynamics over West Africa (Zhang et al. 2017). Short-term forecasts of soil moisture and other parameters to better understand the land-atmosphere interactions on scales of days to years have been developed and are available from the NASA Land Information System based on GPM data along with other precipitation data. Routine LIS data assimilation studies performed at NASA Short-term Prediction Research and Transition (SPoRT) Center have shown that increased land surface model grid resolution (~3 km) can yield an improvement in the estimation of surface model water balance. GPM's data for extreme precipitation leading to flood or landside events, and the characterization of potential hazards, are a source of several GPM investigations (e.g., Panegrossi et al., 2016; Kirschbaum et al., 2017). GPM products have been demonstrated to have positive impacts on precipitation situational awareness for operational forecasters in regions without coverage by ground-based radar systems. GPM's precipitation products continue to inform scientific studies and benefit societal application activities.

Atmospheric Dynamic

NASA continues to make complete atmospheric profiles measurements to better understand atmospheric dynamics. The Atmospheric Infrared Sounder (AIRS) is a high-resolution sounder observing the Earth at 2378 infrared (IR) and four visible channels. It produces vertical profiles of atmospheric temperature, water vapor, atmospheric constituents, cloud properties and surface parameters. AIRS radiances (L1) are routinely assimilated by virtually all global numerical weather prediction (NWP) centers worldwide, and AIRS standard products are widely used by scientists for weather, composition and climate studies, and a variety of societal applications. AIRS is expected to continue operating throughout the Aqua mission.

The AIRS Project and Science Team highest priority items during FY17 have been: a) the detailed validation of the AIRS (IR only) L2 V6 algorithm; b) the initial development, integration and validation of unified L2 retrieval algorithms for AIRS and CrIS; and c) the development, integration and validation of application products using AIRS data – with a focus on drought monitoring.

New discoveries in the context of atmospheric gravity waves continue to be made using AIRS observations. Stephan et al. (2016) used AIRS observations and USArray Transportable Array to study gravity wave processes near two mesoscale convective systems in the Great Plains. AIRS data indicated stratospheric gravity waves propagating away from the location of active convection. Using numerical models and the radar derived latent heating, the study found that deep, intense latent heat release within the storms is the key forcing mechanism for the waves observed at ground level by the USArray.

The AIRS instrument continues to be used to investigate the connection between extreme weather and climate. Wong and Teixeira (2016) examined the cold tails of probability distributions of AIRS brightness temperatures (BTs) at 1231 cm-1 to study the sensitivity of tropical deep convective events to sea surface temperature (SST) changes. The sensitivity is much higher for the coldest BT events than for median events. This study provides global observational evidence of the higher sensitivity of stronger convection and extreme storms to warmer sea surface temperatures.

The AIRS Project and Science Team highest priority items for FY18 will be: a) to finalize Version 7 of the AIRS retrieval algorithm; b) in the context of the new Version 7, to continue the development of a unified AIRS/CrIS L2 retrieval algorithm; c) to monitor and understand the behavior of extreme storms and convection; and d) to continue the development, integration and validation of AIRS application products (with a focus on health applications).

Study of Extreme Events

There are also new missions and instrument developments supporting the research in atmospheric dynamics. The Cyclone Global Navigation Satellite System (CYGNSS) mission was selected as the first Earth Venture Mission (EVM) in 2011. It is using eight micro-satellites to measure wind speeds over Earth's oceans, increasing the ability of scientists to understand and predict hurricanes. Each satellite receives information based on the signals from four GPS satellites.

CYGNSS successfully launched into orbit at 8:37 a.m. EST on December 15, 2016 aboard an Orbital ATK air-launched Pegasus XL launch vehicle. The rocket was dropped and launched over the Atlantic Ocean off the coast of central Florida from Orbital's Stargazer L-1011 aircraft, which took off from Cape Canaveral Air Force Station in Florida. The NASA Launch Services Program, based at the agency's Kennedy Space

Center in Florida, was responsible for spacecraft/launch vehicle integration and launch management.

Several months of engineering commissioning activities followed immediately after launch, for both the eight spacecraft busses and the bistatic radar receiver science payloads. The transition to Phase E (on orbit science phase) of the mission occurred on March 23, 2017, at which time all eight spacecraft were able to operate routinely in science data-taking mode when not being commanded to "high drag" mode for orbit adjustments. The science instruments at this point completed functional performance verification but not science calibration. Once in phase E, the mission began its science calibration and validation (cal/val) phase, which consists of calibration of the Level 1 science data products, tuning of the Level 2 science algorithms, and validation of science data product performance.

In FY2017 the CYGNSS team began regular production of Level 1, 2 and 3 science data products, with delivery to the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) starting on May 22, 2017. The CYGNSS cal/val activities are being conducted, in particular, during the 2017 Atlantic hurricane season that is expected to result in high (storm force) "ground truth" validation wind speed measurements by the NOAA and Air Force hurricane hunter aircraft (specifically, by the dropsondes and Stepped Frequency Microwave Radiometer sensors carried on those aircraft) made at nearly coincident times and locations as CYGNSS overpasses of the Atlantic storms.

A number of papers and reports have been published in this period to document the CYGNSS performance for waves and tropical storms (Clarizia et. al. 2017, Crespo et. al. 2017, Morris and Ruf, 2017a,b), the result from early OSSE experiments (McNoldy et. al. 2017; Zhang et al. 2017), and general concept and outreach (Morris, 2017).

The CYGNSS project plans to continue ongoing cal/val activities as needed in FY2018. It will conduct other ongoing science team investigations, including Data Assimilation and Observing System Experiments associated with improved numerical forecasting of hurricanes; tropical convection and Madden Julian Oscillation studies associated with other (non-cyclone) tropical meteorology; and surface waves and ocean processes studies related to the physical processes forcing ocean surface roughness at small to medium spatial scales.

The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission, selected by NASA in 2016 as part of the Earth Venture–Instrument (EVI-3) program, comprises a constellation of six CubeSats in three low-Earth orbital planes. This observing system is expected to offer an unprecedented combination of horizontal and temporal resolution to measure environmental and inner-core conditions for tropical cyclones on a nearly global scale and provide a leap forward in the temporal resolution of several key parameters (i.e., temperature, humidity, precipitation and cloud properties) needed for assimilation into advanced data assimilation systems capable of utilizing rapid-update radiance or retrieval data.

The TROPICS team accomplished System Requirement Review and Mission Definition Review in FY2017. The Preliminary Design Review is scheduled for late 2017. The first TROPICS Applications Workshop was held in Miami May 8-10. The project is on-track to deliver flight-ready hardware in 2019.

Convective Process Understanding

With the precipitation and atmospheric dynamics sciences maturing, the WFA started to develop new research topics. Suggested by the 2015 Weather Focus Area Report (https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/Weather_Focus_Area_Workshop_Report_2015.pdf), the Convective Process Experiment (CPEX) was competitively selected as part of the Research Opportunities in Space and Earth Science (ROSES) 2016 to help answer questions about convective storm initiation, organization, and growth. After a year of planning and development, CPEX (https://cpex.jpl.nasa.gov/) took place in the North Atlantic-Gulf of Mexico-Caribbean Sea region from May 25 - June 25, 2017, onboard NASA's DC-8 aircraft, based out of Fort Lauderdale, Florida.

Science Objectives include:
- Improve understanding of convective processes, including cloud dynamics and thermodynamics, downdrafts and cold pools, and thermodynamics during initiation, growth, and dissipation.
- Obtain a comprehensive set of observations, especially from Doppler Aerosol WiNd Lidar (DAWN), in the vicinity of isolated and organized deep convection in all phases of the convective life cycle.
- Improve model representations of convective and boundary layer processes over the tropical oceans using a cloud-resolving, fully coupled atmosphere-ocean model.
- Improve data assimilation of the wind, temperature and humidity profiles from the wind lidar and dropsondes into numerical weather prediction models.

During the CPEX, the science team logged 106 flight hours and a total of 16 science missions (91 hours) that covered a wide range of weather conditions from clear and calm wind, isolated convective cloud systems, to Tropical Storm Cindy (2017). It was the first field campaign that collected airborne observations continually from pre-tropical disturbance in the Caribbean Sea, to tropical depression, and subsequent formation of Tropical Storm Cindy in the Gulf of Mexico prior to landfall in Louisiana on June 22, 2017. Eight graduate students participated in the CPEX field campaign and led the real-time forecasting for the flight planning.

The CPEX team is working on data quality control and plans to analyze the CPEX data along with satellite overpasses including GPM, ASCAT, and CYGNSS data, as well as cloud-resolving, coupled atmosphere-wave-ocean model forecast fields in the coming years.

Global Atmospheric Science Synthesis and Weather Forecast Improvement

Atmospheric global general circulation models (GCM) codify our understanding of the atmospheric science, and weather prediction is viewed as a tool to measure our understanding of the weather systems. A model and data assimilation system that performs well in weather prediction is a necessary condition for generating credible atmospheric synthesis (also known as atmospheric reanalysis) products. The Weather Focus Area includes weather prediction exercises and implementation of weather model and data assimilation system improvements with the aim to create the most credible system for process studies and synthetic product generations.

The Global Modeling and Assimilation Office (GMAO) has continued to provide modeling support for NASA's satellite observations. This encompasses the need to examine the impacts of different observation types in weather prediction, and also requires the ability to simulate potential new observation types in order to assess their cost benefit, based on their likely impacts on prediction.

In FY2017 GMAO demonstrated through observation system simulation experiments (OSSEs) the potential value of a fleet of hyperspectral observations on constraining winds by feature tracking (McCarty et. al. abstract submitted to AMS Annual Meeting 2018). The Midwave Infrared Sounding of Temperature and humidity in a Constellation for Winds (MISTiC Wind) concept is an alternative approach to the lidar-based wind measurements. Although the wind measurement with this approach is less accurate, it has the advantage of having much wider coverage than the curtain of measurements obtained from lidar winds. The OSSE demonstrated the beneficial impacts of both the radiance observations and the derived winds in the constellation of MISTiC satellites. The work has also elucidated the potential value of radiance observations in the short-wave infrared (SWIR) part of the spectrum that has previously been investigated using observations from existing satellite instruments (AIRS and CrIS).

In January 2017, GMAO introduced 4D hybrid ensemble variational approach into GEOS Forward Processing (FP) system, along with a resolution increase to ~12km and improved microphysics scheme (Technical Memo in preparation; paper(s) will follow). GMAO also introduced assimilation of skin sea surface temperature (radiances) into GEOS FP system, which had beneficial impacts on the system performance (Akella at el. 2017). Impact studies also demonstrated the value of surface winds from NASA's ISS-based RapidScat instrument (McCarty et al., 2017) for use in real-time systems and in future reanalyses.

Integrity of the GEOS FP system has been demonstrated through participation in field campaigns. Transport characteristics, highlighted by trace gas and aerosols, have been demonstrated in numerous NASA missions, including ATom and ORACLES. Cloud features have been the focus in support of the ABoVE missions over Alaska and northern Canada in summer of 2017. In the late summer and fall of 2015, GMAO participated in

the El-Nino Rapid Response mission, led by NOAA, and the GEOS FP system has been used to assimilate dropsondes over the Pacific Ocean, illustrating the value of such observations on forecasting downstream impacts of the El Nino wind and temperature anomalies (Dole et al., 2017).

For the longer-term prediction, GMAO evaluated impacts of forced and unforced teleconnections on North American precipitation over the western U.S. and impacts of the 2015/2016 El Nino (Lim et al., 2017).

In FY2018 GMAO plans to improve the GEOS FP system in several ways. First, additional enhancements to the underlying model that indicates another notable increase in forecast skill will be introduced. These model upgrades will also include adopting the two-moment cloud microphysics scheme that was initially under consideration for the January 2017 upgrade. Second, a major change is planned to include NASA's GPM-GMI observations that critically depends on both the enhanced representation of clouds and on the use of a 4D assimilation approach. An intense suite of developmental experiments has demonstrated the value of all-sky radiance measurements from the GPM-GMI instrument in a developmental version of the GEOS assimilation system; this work demonstrates not only the added benefits of NASA's research datasets in NWP systems, but also pioneers the introduction of the all-sky (cloud- and aerosol-contaminated) radiance observations in the analysis code that is used by both the GMAO and the National Weather Service.

The Joint Center for Satellite Data Assimilation (JCSDA) is a multi-agency (NASA, NOAA, USAF, and USN) collaborative effort that supports scientific development in multiple areas for the purpose of accelerating and optimizing the assimilation of satellite data in operational environmental prediction modeling systems. NASA's GMAO is the primary contributor and beneficiary of the JCSDA. The GMAO conducts its own internal projects, some of which are directly related to the JCSDA projects and science priorities. NASA also funds JCSDA for specific developments that NASA would later integrate into the GEOS modeling and data assimilation systems. In addition, the JCSDA supports external research funded via grants and contracts awarded through competitive processes open to the broader scientific community. It is essential that all these efforts be complementary to and coordinated with one another.

The JCSDA has gone through a significant change this year, adopting the following six primary scientific priority areas, approved by the JCSDA Science Steering Committee:

- Radiative transfer modeling
- Preparation for assimilation of data from new instruments
- Assimilation of humidity, clouds, and precipitation observations
- Assimilation of land surface observations
- Assimilation of ocean surface observations
- Atmospheric composition, chemistry and aerosol

In FY2017, the JCSDA has begun to manage these efforts through a set of Project Teams,

including:

- Community Radiative Transfer Modeling (CRTM)
- New and Improved Observations (NIO)
- Sea-ice, Ocean, Coupled Assimilation (SOCA)
- Joint Effort for Data assimilation Integration (JEDI)
- Impact of Observing System (IOS)
- Global Forecast Dropout Prediction Tool (GFDPT)

A JCSDA annual operating plan, which lays out specific tasks for the year, has been developed in FY2017 and GMAO has identified specific areas of developments including the improved physical representation for aerosols, clouds, precipitation, and land surface, acceleration of CRTM computations, encapsulated observation operator, and interface for observation data access (IODA).

Short-term Weather Prediction and Transition to Operations

The Short-term Prediction Research and Transition (SPoRT) Center continued to serve in its critical role as facilitator for the transition of unique observations and research capabilities to the operational weather community to improve short-term forecasting. With the launch of the GOES-R satellite, SPoRT has developed a plan to serve the geostationary satellite user community with the GOES data, with emphasis on the Advanced Baseline Imager (ABI). SPoRT installed a GOES rebroadcast antenna and Community Satellite Processing Package (CSPP) processing system to receive the data in near real time. The plan is to apply MODIS algorithms to the ABI data to generate high-resolution atmospheric and land surface products.

In FY2017 SPoRT has contributed to the transition of Geostationary Lightning Mapper (GLM) and ABI observations from the new GOES-16 weather satellite to operational forecasters at the NOAA National Weather Service (NWS) (Fuell et al. 2016; Berndt et al. 2017; Terborg et al. 2017). Working with COMET, SPoRT developed training for specific GLM products, discussing the strengths and weaknesses, with the goal of successfully transitioning products to operations. It completed transition of precipitation rain rate measurements from the Global Precipitation Measurement (GPM) mission to several NWS Weather Forecast Offices and River Forecast Centers in the southwest U.S. and Alaska. Through targeted assessments with operational forecasters in this region, SPoRT has identified a number of valuable examples where precipitation data from GPM were used by forecasters to improve extreme precipitation and hydrological guidance. SPoRT has completed integration of retrieved soil moisture observations from the NASA Soil Moisture Active/Passive (SMAP) mission into an offline version of the NASA Land Information System (LIS) and is currently tuning the model to improve impacts. SPoRT led the first TROPICS Application Workshop in May 2017 in anticipation of the launch of TROPICS small satellites to discuss the potential usage of data for various applications.

SPoRT plans to continue support of GLM and value-added multispectral ABI imagery transition and engage with new U.S. partners who have weather-related operational challenges. Assessments with NWS forecasters are planned whereby operational impacts will be determined. Additional applications training materials will be generated as part of these interactions with forecasters. SPoRT will conclude SMAP data assimilation activities in FY2018 and investigate impacts on numerical weather prediction and hydrologic models. LIS soil moisture analyses will be linked with SMAP data assimilation to the Weather Research and Forecasting model in a configuration similar to the NOAA NWS High Resolution Rapid Refresh to demonstrate impacts on convective initiation and severe weather.

SPoRT will continue to expand transition of GPM data to other coastal NWS users beyond Alaska (e.g. Pacific Region, Western Region) to use data as a supplement to ground-based radar and gauge systems.

Progress Assessment and Advanced Planning

PMM Science Team Meeting, October 24 – 28, 2016
The 2016 Precipitation Measurement Mission (PMM) Science Team meeting (https://pmm.nasa.gov/meetings/all/2016-pmm-science-team-meeting) consisted of general oral and poster sessions covering mission/program status, partner reports, science activities, field campaign results, and other science team business. Algorithm team meetings were held on October 27. Participants of the NASA-JAXA Joint PMM Science Team (JPST) participated in a JPST meeting on October 28, 2016. Other algorithm and working group meetings also took place throughout the week to discuss various algorithm implementation issues and priorities for the GPM mission.

Wind Lidar Working Group Meeting, March 21 – 23, 2017
The Working Group on Space-based Lidar Winds met on March 21-23, 2017 in Newport News, Virginia. The meeting included approximately 75 participants from NASA centers, NOAA, industry and Japan, discussing a variety of topics, including recent technology advancements, recent and future field studies and technology developments, and potential space-based instruments. A delegation from Japan attended the meeting to report on Japanese space-based wind lidar activities and to discuss potential future collaborations. Lively discussions took place on a variety of topics, including the importance of full-troposphere versus boundary layer profiles, synergisms with currently available techniques such as atmospheric motion vector derived winds, and appropriate reporting of instrument accuracy and precision. The group agreed to meet again in the fall at a western U.S. location. Agenda, attendance list, and presentations from the workshop can be accessed at the Working Group website: http://cires1.colorado.edu/events/lidarworkshop/LWG/.

AIRS Science Team Meeting, April 17-18, 2017
The Atmospheric Infrared Sounder (AIRS) Spring Science Team meeting (https://airs.jpl.nasa.gov/events/38) consisted of a few invited presentations and working group discussions focusing on one key question: Which science questions are essential to

address with the 40-year record of IR sounder observations that are currently available and planned for the future? With this focus, the meeting was able to be more forward looking and explicitly covered climate, weather, and composition science topics related to current and planned IR sounders.

TROPICS Application Workshop, May 8-10, 2017
NASA Earth Science Division Applied Sciences Program convened the first TROPICS Applications Workshop to enable a conversation between the mission developers/science team and the end-user/applications community. A comprehensive 2.5-day agenda was assembled by the organizing committee that encompassed two panel discussions, four applications-focused sessions, and two breakout sessions. The panel discussions focused on how TROPICS can leverage lessons learned from other satellite missions and how TROPICS fits into the broader Earth satellite community. The applications sessions focused on potential operational or application areas of TROPICS data related to the core science team measurements and products: 1) Terrestrial, 2) TC Nowcasting, 3) Modeling and Data Assimilation, and 4) Tropical Dynamics. The objective of the breakout sessions was to collect broader inputs on strengths and limitations of the mission concept for applications and to identify potential new applications areas where TROPICS data could be used for applied research and operational decision making.

By fulfilling these specific objectives before final mission formulation and two to three years prior to the expected mission launch date, the TROPICS Science Team demonstrated a commitment to maximize return on investment for NASA by pushing for impact on application end-user decisions. Further, inputs provided during this applications workshop will be used to help finalize some of the mission implementation decisions in preparation for Preliminary Design Review.

More information on the meeting, including presentations and summary of breakout discussions can be found at: http://tropics.ccs.miami.edu

15th JCSDA Technical Review & Science Workshop on Satellite Data Assimilation, May 17-19, 2017
The JCSDA Technical Review Meeting and Science Workshop aims at facilitating the coordination among the member agencies and research and development efforts funded by these organizations, and is conducted to assess the ongoing and planned scientific development sponsored by the JCSDA. Two full and one-half days were devoted to the meeting, with ample time for informal discussions, interactions, and scientific exchanges, as well as for formal presentations, both among scientists from all JCSDA partners and with JCSDA managers. Recommendations from project team discussions that took place during the meeting will be reviewed by the JCSDA management, and will serve as one of the inputs when developing technical directions of the JCSDA future activities.

The workshop information, including presentations, is available at: https://www.jcsda.noaa.gov/meetings_Wkshp2017.php.

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FY 2017 Annual Performance Indicator	FY 14	FY15	FY16	FY17
ES-17-3: Demonstrate planned progress in improving the capability to predict weather and extreme weather events. Progress relative to the objectives in NASA's 2014 Science Plan will be evaluated by external expert review.	Green	Green	Green	Green

Annual Performance Indicator ES-17-6: Demonstrate planned progress in detecting and predicting changes in Earth's ecological and chemical cycles, including land cover, biodiversity, and the global carbon cycle.

NASA research in the Carbon Cycle and Ecosystems focus area continues to increase knowledge of changes in Earth's biogeochemical cycles, ecosystems, land cover, and biodiversity. Suborbital and satellite observations are used to detect and quantify these changes and, when used within numerical models, to improve our ability to assess impacts, identify feedbacks, and predict future changes and consequences for society. The research is a balance between global and regional studies, with local studies providing insight into important processes that elucidate the region's unique role in the Earth system. Highlights of research conducted in the past year are summarized below.

Critical Regions of the Earth System

The world's Arctic and boreal regions are experiencing significant environmental change. Satellite and airborne remote sensing data allow us to monitor and assess a wide range of ecological processes and determine how they are changing at a range of spatial and temporal scales (Brown et al. 2016).

High latitude (the Arctic and Southern Ocean) marine ecosystems play a key role in the carbon cycle by uptaking significant amounts of anthropogenic CO_2 through primary production and exporting it to depth as organic matter. High latitudes are also regions that are undergoing dramatic changes such as warming, stratification and loss of sea ice. Research conducted over the past year with in situ ship-based and autonomous observations, as well as with satellite remote sensing, has helped advance the understanding of the dynamics of marine phytoplankton, biogeochemical cycling and carbon export, which are critical to predict the impact of changing ocean conditions to high latitude ecosystems (e.g. Balch et al., 2016; Behrenfeld et al., 2017; Haëntjens et al., 2017).

Coordinated research in this region carried out as part of the Arctic-Boreal Vulnerability Experiment (ABoVE) field campaign has documented the extent of warming and degradation of permafrost (Liljedahl et al. 2016), as well as the linkages between fire and permafrost dynamics (Brown et al. 2016). They have also provided an improved understanding of the seasonal dynamics of emissions of carbon dioxide and methane from tundra, where significant autumn and winter emissions have been documented (Commane et al. 2017). These emissions have increased 73% (±11%) since 1975 and are correlated with increasing summer temperature. Furthermore, spatial variability in vegetative cover driven by variability in disturbance regimes and/or topography also has a large impact on permafrost dominated landscapes.

A number of different mechanisms and processes have been identified as being important regulators of the terrestrial carbon cycle. Spaceborne lidar data were used to study variations in canopy and understory structure in Amazon tropical forests to understand factors influencing light-driven growth during the dry season (Tang and Dubayah 2017). Lidar data showed that both the understory and canopy were responding to variations in light conditions and moisture regimes. Additional studies on using advanced tomographic SAR techniques for forest canopy structure and aboveground biomass were carried out

using UAVSAR data from the AFRISAR field campaign conducted in 2016 in Gabon. Planning for coordination of field data needed for calibration/validation of three future NASA biomass missions was carried out (NASA/ISRO [Indian Space Research Organizations]– NISAR; NASA's Global Ecosystem Dynamics Investigation [GEDI]; and ESA's BIOMASS missions).

At the global scale, modeling studies showed that during the recent warming period from 1980-1992, increased net biome productivity was due to decreased heterotrophic respiration, not increased primary production (Ballantyne et al. 2017). It was also shown that at both local and regional scales, water availability is a strong regulator of both gross primary productivity and terrestrial ecosystem respiration (Jung et al. 2017).

Marine Biogeochemistry and Ecology

The ocean is an important component of the climate system, and exchanges important gases and aerosols with the atmosphere. This exchange is driven by physical and biogeochemical processes which are variable at the same time impact the biogeochemistry and biology of the ocean. Research carried out over the past year through the use of *in situ* data, modeling and remote sensing has advanced the current state of knowledge on globally integrated rates of ocean carbon uptake, and improved the ability to understand present variability and predict future states of the global carbon cycle (e.g. McKinley et al., 2017; Fay et al., 2017).

Phytoplankton are an essential component of the marine food webs, and play a critical role in global biogeochemical cycles. Understanding changes in the composition of phytoplankton populations, as well as variations in net primary production, are essential to improve the current understanding of how ocean biology may respond to climate forcings. Over the past year, research focusing on global and local phytoplankton trends measured from satellites (e.g. Kahru et al., 2017; Gregg et al., 2017) improved net primary production models, and novel techniques for how to better measure chlorophyll in situ (e.g. Nardelli and Twardowski, 2016; Roesler et al., 2017) have advanced knowledge on the current state of Earth's phytoplankton, the foundation of ocean food webs and a key component of the marine carbon cycle. In addition, recent research has also focused on the intensification of harmful algal bloom appearances, which impact human health (Urquhart et al., in press), and on the increase of floating macroalgae, such as *Sargassum*, which can lead to environmental and economic problems for coastal communities when it beaches (Wang and Hu, 2017).

NASA supports several airborne and combined airborne/field campaigns that contributed to the assessment of marine biogeochemistry and ecological resources. The COral Reef Airborne Laboratory (CORAL; https://coral.jpl.nasa.gov) project will provide detailed data needed for a better fundamental understanding of how coral reef ecosystems function by combining airborne remote sensing data from PRISM (Portable Remote Imaging Spectrometer) and in-water measurements to produce the first comprehensive assessment of reef condition. Over the past year, CORAL completed field work which included representative sites across the Pacific Ocean. Observations taken by the North Atlantic Aerosols and Marine Ecosystems Study (NAAMES; http://naames.larc.nasa.gov) combine airborne and ship, with continuous satellite and *in-situ* ocean sensor records, improving predictive capabilities of Earth system processes and informing ocean management and assessment of ecosystem change. The third NAAMES cruise in the

North Atlantic commenced on August 30, 2017 with a five-week duration. The EXport Processes in the Ocean from RemoTe Sensing (EXPORTS; https://cce.nasa.gov/ocean_biology_biogeochemistry/exports/index.html) campaign is designed to advance the utility of NASA ocean color assets to predict how changes in ocean primary production will impact the global carbon cycle. Successful research proposals that comprised the EXPORTS science team (ST) were announced in early July 2017, and the project kicked off with an official meeting in September 2017. Finally, in the Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM), NASA added bio-optical sensors to approximately fifty ocean floats funded under the National Science Foundation's SOCCOM program. SOCCOM's mission is to drive a transformative shift in the scientific and public understanding of the role of the Southern Ocean in climate change and ocean biogeochemistry. All of the data derived from this project is freely available through the SOCCOM database:http://soccom.princeton.edu/content/float-data.

Disturbance in Terrestrial Ecosystems

Satellite remote sensing data collected over the past two decades has been used in combination with longer-term fire management records to study changes in area burned during human-caused and lightning-ignited fires (Andela et al. 2017). While human activities related to the intensification of agriculture have resulted in a decrease in burned area globally over the last 18 years, an increase in human ignitions along with a warming climate are key contributors to increased wildfire area burned in the western U.S. (Abatzoglou and Williams 2016). In the western boreal forest region of North America, increased wildfire activity has been linked to increases in lightning ignitions as well as warming conditions and extended fire seasons Veraverbeke et al. 2017).

New approaches continue to be developed and evaluated to not only map terrestrial disturbances using satellite remote sensing data, but to determine the specific causes of the disturbances (Schroeder et al. 2017), information that is critical for understanding their impacts. Use of remote sensing data provides information on specific areas that re-burn in regions experiencing increased fire activity, and how fires influence shifting vegetation, directly impacting the carbon cycle. In Alaskan boreal forests, areas experiencing more frequent burning are losing legacy carbon stored in surface organic materials and shifting from conifer to deciduous forests (Hoy et al. 2016).   The floodplain forests of the Amazon were converted to non-forests dominated by herbaceous vegetation after only two repeat fire events (Flores et al. 2016).

North American Teleconnections of Climate, Carbon and Water

An improved understanding of changes to vegetation at regional and global scales has been gained through studying both teleconnections between a warming Arctic and cooler conditions at mid-latitudes, as well as linkages between climate change and the hydrologic cycle. Changing large-scale atmospheric circulation has linked warming spring temperatures in the North American Arctic with cooler spring temperatures in mid-latitudes, which in turn has lowered terrestrial primary productivity, including lower crop yields by up to 20% in some states (Kim et al. 2017). It was found that gross primary production in two-thirds of the global vegetated area was correlated to groundwater table depth during at least one season (Koirala et al. 2017). In the southwest

U.S., primary production in higher elevation montane forests was less affected by drought conditions than were lower elevation desert ecosystems (Herrmann et al. 2016).

Remote Sensing Advances for the Carbon Cycle and Biodiversity

A Landsat 8 Operational Land Imager (OLI) atmospheric correction algorithm was developed using the Second Simulation of the Satellite Signal in the Solar Spectrum Vectorial (6SV) model, refined to take advantage of the narrow OLI spectral bands (compared to Thematic Mapper/Enhanced Thematic Mapper (TM/ETM +)), improved radiometric resolution and signal-to-noise. In addition, the algorithm uses the new OLI Coastal aerosol band (0.433–0.450 μm), which is particularly helpful for retrieving aerosol properties, as it covers shorter wavelengths than the conventional Landsat, TM and ETM + blue bands (Vermote et al., 2016). Similarly, Roy et al. (2016) used ordinary least squares regressions (OLS) to quantify linear differences between the two Landsat sensors used by Vermote et al. (2016). New regression coefficients were provided to user communities for their research (Roy et al, 2016).

A number of new approaches and sensors are being developed and evaluated to use remote sensing to measure plant photosynthesis. It was determined that satellite observations of solar-induced chlorophyll fluorescence (SIF) provided a more direct proxy for photosynthesis than satellite-based vegetation indices when used as inputs to models of net primary productivity for tundra ecosystems (Luus et al. 2017). The use of airborne SIF data has allowed development of a clearer understanding of how this new measurement approach relates photosynthesis to daily variations in environmental conditions and forest stand structure, as well as the importance of the various SIF bands (Middleton et al. 2016). Using MODIS data, a chlorophyll/carotenoid index was shown to be highly correlated to the seasonal patterns of daily gross primary productivity of evergreen conifer stands measured by eddy covariance (Gamon et al. 2017). As part of a NASA-ESA collaboration on the planned ESA fluorescence mission, FLEX, coordinated airborne-ground campaigns were conducted by NASA in tropical forests (Puerto Rico) and temperate forests (Maryland) to better understand the role of sensor geometry and canopy architecture on airborne fluorescence measurements (Middleton et al. 2016). ESA has focused primarily on agricultural systems while NASA has focused on forests.

Though remotely-sensed chlorophyll concentrations in the ocean are based on variations in ocean color, the impact of physiological processes on such ocean color retrievals is often overlooked, as well as the three-dimensional structure of phytoplankton blooms. This may affect our assessment of global phytoplankton productivity and estimation of chlorophyll. In addition, understanding the relationship between light availability, physiology, and how energy is utilized may provide additional information on the photophysiological state of the phytoplankton population. Recent advances on variable chlorophyll fluorescence measurements, pathways and spectral nature of light (e.g. Lin et al., 2016; Gregg and Rousseaux, 2016), as well as novel phytoplankton measurements using lidar (e.g. Schulien et al., 2017), are paving the way towards improved phytoplankton stock and NPP calculations, and will be able to provide further insight on the efficiency of phytoplankton to absorb light for photosynthesis; this will provide better constraints on the impact of physiological changes on net primary production.

Protecting global species from environmental change necessitates an ability to monitor elements of biodiversity and the influence of the surrounding environment on biological

function. New remote sensing techniques are being developed to allow detection of these phenomena over whole regions and are generally less laborious and costly than using traditional methods. These projects develop innovative remote sensing capabilities to address this goal (Cavender-Bares et al. 2016, Hobi et al. 2017, Zhu et al. 2017).

Urban Ecosystems

Urban heat islands (UHIs) have been long studied using both ground-based observations of air temperature and remotely sensed thermal infrared (TIR) data. While ground-based observations lack spatial detail even in the occasional ''dense'' urban network, skin temperature retrievals using TIR data have lower temporal coverage due to revisit frequency, limited swath width, and cloud cover. Algorithms have recently been developed to retrieve near-surface air temperatures using microwave radiometer data, which enables characterization of UHIs in metropolitan areas, major conurbations, and global megacities at regional to continental scales using temporally denser time series than those that have been available from TIR sensors. In a recent study (Nguyen and Henebry, 2016) surface air temperatures derived from the AMSR-E onboard Aqua and AMSR2 onboard JAXA's GCOM-W1 satellites were compared with station observations from the Global Historical Climate Network (GHCN) for 27 major cities across North America. Accumulated diurnal and nocturnal degree-days, calculated from the remotely sensed surface air temperature time series, were used to characterize the urban-rural thermal differences over multiple growing seasons. Daytime urban thermal accumulations from the microwave data were sometimes lower than in adjacent rural areas. In contrast, station observations showed consistently higher day and night thermal accumulations in cities. Results show that while urban-rural thermal gradients may vary according to different datasets or locations, day-night differences in thermal time metrics are consistently lower in urban areas than in rural areas. The study concludes that the special accumulated thermal time index is a more robust metric for comparative UHI studies than simple temperature differences because it can be calculated from either station or remotely sensed data and it attenuates latitudinal effects.

 Other studies, focused on the feedbacks between urban land cover and urban climate, have shown that the urban heat island effect can impact both surface temperature and vegetation phenology as far as 15 km from an urban core (Melaas, et al., 2016). Moreover, increases in impervious surface are associated with increases in both surface temperature and vapor pressure deficit. UHIs are more pronounced at night and urban-rural groupings exhibit higher accumulated nocturnal degree-days in cities (Wang et al., 2017). The surface urban heat island effect is found to be reduced by the presence of forest patches, demonstrating the importance of urban forests to moderating the heat island effect. Species composition, land cover patterns, and vegetation patch sizes all influence both urban vegetation phenology and the urban surface climate.

Several atmospheric modeling case studies reveal the complexities of designing effective urban heat mitigation strategies. Studies suggest that policy-makers can optimize the performance of their urban heat mitigation policies and programs, starting with a thorough understanding of the actual end-point goals of these policies, and integrating scientific knowledge into the development of location-specific strategies that recognize and address the key limitations of planning and policy initiatives to mitigate extreme urban heat (Sailor et al., 2016, Oyuang, et al., 2016).

To facilitate urban research as described above, two global, 30-m inter-related data sets, the Global Man-made Impervious Surfaces (GMIS) and Human Built-up and Settlement Extent (HBASE) from Landsat-derived surface reflectance data have been generated and processed at the University of Maryland. These datasets are freely open and available at the Socioeconomic Data and Application Center (SEDAC; http://beta.www.ciesin.columbia.edu/mapping/impervious-surfaces/).

Species Management and Case Studies in Climate and Biodiversity

Earth observations have an unprecedented potential to improve understanding of where species currently are and why, as well as how the range of species of great concern may change. Alongside modeling frameworks, remotely sensed data can quantify and forecast environmental changes that affect species' habitat and contribute to the development of effective and sustainable resource management strategies. These NASA-funded studies partner with communities, such as natural resource managers (both land and marine) and those involved in conservation and sustainable ecosystem management, to facilitate informed public and private decision making (Jantz et al. 2016, Neville et al. 2016, Witharana, et al. 2016, Sutton and Lakshmi. 2017, Wade, et al. 2017).

Climate change is anticipated to alter the range of species, and for many species it will also result in population declines that could reduce long-term viability. Negative impacts can result from many pathways, including degraded habitat and physiological effects of warming. Not all species respond to the same climate or environmental cues or are equally affected by the same phenomena. NASA-funded studies highlight the need for diverse satellite remote sensing observations and models to track the varied impacts of climate change on biodiversity (Reed et al. 2016, Regehr et al. 2016, Hurley et al. 2017, Rogers et al. 2017).

From mid-January through very early March, NASA flew one of its ER-2 high-altitude aircraft in Hawaii with two instruments aboard, the Airborne Visible/Infrared Imaging Spectrometer-Classic (AVIRIS-Classic) spectrometer, operating in the visible to shortwave infrared wavelengths of the electromagnetic spectrum, and the MODIS/ASTER (MASTER) Airborne Simulator instrument, which includes imaging bands in the thermal infrared region of the spectrum. This airborne campaign focused on observations of coral reefs and volcanoes in the Hawaiian Islands. Oahu's Kaneohe Bay was the location for many *in situ* observations of coral reefs during the ER-2 flights. Six associated coral reef research projects focused on reef health and the ability of imaging spectroscopy to characterize reefs and their optical properties, as well as those of their surrounding environments, at varying spatial resolutions.

Workshops and Collaborative Activities

The International Workshop to Reconcile Methane Budgets in the Northern Permafrost Region was held in Seattle on 7-9 March 2017. The workshop was funded by a NASA Topical Workshop, Symposia, and Conferences (TWSC) award, as well as by the NSF, the U.S. Geological Survey, and the U.S. Arctic Research Commission. The primary goal of the workshop was to produce a plan for reconciling methane budgets in the northern permafrost region. The workshop was attended by 42 scientists and included representatives of the atmospheric, land (wetland and lakes), coastal, and remote sensing communities studying methane dynamics in this region. This workshop highlighted the

need to organize methane data for the northern permafrost region so that studies can evaluate how to improve the estimates of methane emissions and the detection of trends in methane emissions across the region. Furthermore, the CC&E Focus Area initiated three new Inter-Disciplinary Studies projects on methane focusing at the global scale, the U.S. Corn Belt, and Amazonian aquatic systems, respectively.
Ocean Biology and Biochemistry contributed to an annual summer Ocean Carbon and Biogeochemistry workshop, which was held in Woods Hole, MA from June 26-29, 2017 and focused on thematic topics including carbon fluxes, physical-biological-biogeochemical interactions, and ecological and biogeochemical impacts of natural climate perturbations (http://www.us-ocb.org/summer-workshops/2017-ocb-summer-workshop-archive/).

In March and August 2017, the Biodiversity program supported workshops bringing together experts working under the umbrella of the Marine Biodiversity Observation Network (MBON) to generate a demonstration product to address one or more specific targets of the United Nations Sustainable Development Goal 14 "Conserve and sustainably use the Oceans, Sea and Marine Resources for Sustainable Development." These MBON products are currently being validated for implementation as a demonstration at the October 2017 GEO XIV Plenary Session. The final products will be housed on a public web site to facilitate community usage.

The Land-Cover/Land-Use Change (LCLUC) program is supporting the South/Southeast Asia Research Initiative (SARI), which holds regular international regional workshops in South/Southeast Asia, typically attended by 100-150 participants from 15-20 countries. The purpose of the meetings is to provide a forum to discuss LCLUC and its impacts around the following themes: (1) agriculture and water resources, 2) biomass burning, including land-atmosphere interactions, 3) urbanization, 4) land use in coastal zones and estuaries, and 5) land use in forests and mountain regions. Overview presentations share recent research accomplishments and the state of the art on these topics, and formulate future research directions and applications development needs for the region. The meetings are used to explore opportunities for coordination and collaboration among research scientists and teams aimed to advance understanding of the spatial extent, intensity, social consequences, and impacts on environment in the region. Coordination with the NASA-USAID SERVIR activities in its two nodes in Asia (the Himalaya node and the Mekong node) and enhancement of the existing network based on the SARI projects is one of the goals. Early career scientists attending also participated in two- or three-day hands-on training sessions focused on the use of remote sensing and geographic information systems (GIS) for regional applications using MODIS, Landsat, Sentinel-1 and -2 and other sensors' observations. The meetings are organized and sponsored as joint initiatives of the LCLUC Project Office at the University of Maryland College Park, the global change SysTem for Analysis, Research and Training (START) international program, and the Global Observation for Forest and Land Cover Dynamics (GOFC-GOLD) Program, with additional in-kind sponsorship from a hosting organization. During the last year, the following workshops were conducted: 1) October 2016 in Ho Chi Minh City, Vietnam, 2) May 2017 in New Delhi, India, and 3) July 2017 in Chiang Mai, Thailand.

Land-cover/land-use observations are an essential part of NASA's core mission. Promotion of the data and data products from the Landsat mission and development of its complementary use jointly with space assets of NASA's partners is fundamental to NASA's activities. Landsat data alone are often insufficient in some applications when more frequent observations are needed, e.g., in agriculture monitoring. Significant funds have been invested during the last several years to investigate synergistic use of Landsat data with non-U.S. assets, especially from the ESA Sentinel program. At SARI workshops, we discuss the use of other sensors with similar spatial resolution making observations in the South/Southeast Asia region. Only through international coordination can we fully address the observations, science, and coordination mechanisms that will optimize our collective ability to serve our communities.

The collapse of socialism in Eastern Europe in the late 1980s and early 1990s represents one of the most dramatic changes of entire societies the World has ever witnessed. In short order, the cold war ended, political regimes changed, institutions toppled, and economies collapsed. Not surprisingly, this had major environmental consequences, most notably due to rapid and unprecedented changes in land use, including widespread agricultural abandonment.

Gutman and Radeloff (2017) is the first comprehensive review of these land-use changes and their environmental consequences. It compares and contrasts the different countries of Eastern Europe, all of which changed, but each in its unique way. And ultimately, it highlights the importance of understanding socioeconomic shocks, i.e., those brief periods during which societies change rapidly, resulting in significant impact on land use and the environment, and thus showing that change is often abrupt rather that gradual and thereby hard to predict.

The book is the fourth in the series describing land-cover and land-use changes occurring in various parts of Northern Eurasia based on the studies conducted under the NASA LCLUC program in the Northern Eurasia Earth Science Partnership Initiative (NEESPI) framework. The first three discussed LCLUC in the 1) Arctic region, 2) Siberia and 3) Drylands of East Asia. The current book describes and analyzes the effects of the collapse of socialist governance and management systems on land cover and land use in various parts of Eastern Europe, including countries of the former Soviet Bloc, former Soviet Union republics, and European Russia. This book is a compilation of the results from studies on LCLUC and their interactions with carbon cycle and environment, effects of institutional changes on urban centers and agriculture, as well as wildlife populations. The book is a truly international interdisciplinary effort written by an international team consisting of scientists from the U.S., Europe, and Russia under the auspices of NEESPI, supported by the NASA LCLUC Program.

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FY 2017 Annual Performance Indicator	FY 14	FY15	FY16	FY17
ES-17-6: 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-16-7:</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's Water and Energy cycle focus area (WEC) continues to improve our understanding of the water cycle by developing tools that contribute to a better evaluation of the global water cycle budget and improved assessment of water quality, both of which can help enable improved water resource management. The focus area science community uses satellite and airborne remote sensing observations to improve our understanding of physical processes, the transfer and storage of energy and water in the Earth System, to enhance models and detect and quantify changes in the Earth System. These objectives are accomplished through two separate programs within the Water and Energy Cycle Focus Area: NASA Energy and Water Cycle Study Program (NEWS: http://nasa-news.org) and the Terrestrial Hydrology Program (THP). NEWS aims to resolve all fluxes of water and the corresponding energy fluxes involved with water changing phase. The THP studies the hydrologic processes associated with runoff production, fluxes at the land-air interface, terrestrial water stores (surface water, seasonal snowpack, soil moisture, and groundwater), and extreme hydrological events. THP also fosters the development of hydrologic remote sensing theory, the scientific basis for new hydrologic satellite missions, and hydrologic remote sensing field experiments. Developed WEC capabilities are also quantified and assessed to enable better handoff to the decision-making community.

Water & Energy Cycle Focus Area research addresses the following overarching questions identified in the NASA Energy and Water Cycle Study Road Map (http://nasa-news.org):

- How will water cycle dynamics change in the future?
- How are global precipitation, evaporation, and the cycling of water changing?
- What are the effects of clouds and surface hydrologic processes on Earth's climate?
- How are variations in local weather, precipitation, and water resources related to global climate variation?

These questions require systematic knowledge/quantification of each water cycle element to determine the global water budget and requires the ability to measure and track the energy exchange when water changes phase. Current and planned NASA missions seek to measure water in storage and in transit: WEC research will advance our global understanding of water and energy budget and cycle based on these measurements. Below are highlights of WEC Focus Area funded research accomplishments for FY2017.

<u>Global precipitation, evaporation, and the cycling of water</u>

The water and energy cycle leverages the investments of other focus area programs to create, refine, and use long time scale assessments related to precipitation and ocean-air interaction. One of the objectives is to provide insight on how fusing and integrating varied data sets supports the analysis of different types of scientific research (e.g. trend detection/analysis, model evaluation, extreme events, etc.). This also enables focus area researchers to jointly investigate precipitation, or ocean surface fluxes, etc. with other components of the global water cycle.

Global precipitation variations over the satellite era are reviewed by Adler et al. (2017) using the Global Precipitation Climatology Project (GPCP) monthly, globally complete analyses. Global precipitation variations, during the satellite era, have small increases during El Niño events and noticeable decreases after major volcanic eruptions. While the research found no overall significant trend in the global precipitation mean, they did find that there is a pattern of increased rainfall over tropical oceans and decreased rainfall over some middle latitude regions. These observed patterns result from a combination of inter-decadal variations and global warming during the study period (1979-2014).

Schumacher (2017) released a survey that enhances access to global precipitation information, especially enabling research into the causes and quantitative assessment of heavy precipitation, which has become necessary as researchers investigate processes on small spatial scales and decision makers attempt to mitigate the effects of flash flooding. They have created a compendium of research as an initial step to easy access on-line resources of data pertinent to studies on (heavy) precipitation and (flash) flooding, especially as they are connected to other parts of the global water cycle (i.e. atmospheric water vapor).

A study by Krishnamurti et al. (2017), using daily data sets of ocean heat content (OHC) for a 17-year period covering each of the summer monsoon seasons, found a robust intraseasonal oscillation (ISO) signal in the Bay of Bengal (BoB) OHC anomaly. This ISO signal propagates northward at the rate of roughly one degree latitude per day and has a lag of roughly 4 to 6 days from the appearance of the signal in the surface wind speed. The study examined the possible relationship of the ISO signal in the OHC with other parameters, such as surface wind (i.e. speed, stress curl, and related upwelling/downwelling), sea surface temperature (SST), net surface heat flux into the ocean, and surface rain. The study also assimilated other data, such as river runoff and precipitation, to show a robust ISO time scale and explain the lag relationship (of 4-6 days) as related to strong winds that cool the ocean.

Huang et al. (2016) produced a dataset of global (1°x1°) surface fluxes, with three-hour increments, for the period 2001 to 2010, which contains ocean surface heat fluxes and snow/ice surface heat fluxes for the Arctic and Antarctic regions. This dataset was used as input to their maximum-entropy-production (MEP) model to re-estimate global surface heat fluxes. When predicting surface fluxes, their MEP model automatically balances the surface energy budgets at all time and space scales without the explicit use of near-surface temperature and moisture gradient, wind speed, and surface roughness data. Their land MEP model uses surface radiation, temperature data (NASA CERES), and MERRA surface specific humidity data to produce an estimate of terrestrial evapotranspiration that agrees closely with previous estimates. However, their estimate of ocean evaporation is lower than previous estimates, while their estimate of ocean heat

flux is higher than previously reported. The MEP model produces the first global map of ocean surface heat flux that is not available from existing global reanalysis products.

Variations in local weather, precipitation, and water resources

WEC funds research to characterize variations in local weather patterns, precipitation, and water resources over time to identify and understand the mechanisms driving the hydrologic variability. This is accomplished through the integration of remote sensing imagery with in situ datasets, comparative analysis, and numerical models to establish baseline understanding of varied hydrological systems. Studying these systems over time enables us to understand if the variability is part of a stable cyclic process, influenced by anthropogenic activity, or if the variability is in response to long-term climatic factors. There were several studies that advanced our knowledge of 'atmospheric rivers,' informally known as Pineapple Express, which are long, narrow filaments of large vertically-integrated water vapor that concentrates the water content of a typical hurricane with wind speeds to match into a narrow (~100 km wide) 'firehose.' Atmospheric Rivers contribute between 30-50% of a region's annual water budget and are responsible for 90% of the poleward transport of moisture to high latitudes. Atmospheric Rivers (ARs) are found globally with significant influence on the west coasts of the United States, Europe and North Africa.

A study, by Waliser and Guan (2016), published in Nature Geosciences, found that ARs comprise half of the top 2% of the most extreme precipitation and wind distribution events across most mid-latitude regions globally. Atmospheric rivers that make landfall are associated with about 40 to 75% of extreme wind and precipitation events over 40% of the world's coastlines. Atmospheric rivers are associated with a doubling (or more) of the typical wind speed and precipitation amounts compared to all storm conditions, and with a 50 to 100% increase in the probability for an extreme. They found that the majority of extreme wind events catalogued between 1979 and 2013 over Europe with billion $US losses were associated with atmospheric rivers. They concluded that landfalling ARs represent a significant hazard around the globe, because of their association with not only extreme precipitation, but also extreme winds.

Rain-on-Snow (ROS) events during ARs present enhanced flood risks due to the combined effect of rainfall and snowmelt. Guan et al. (2016) focused on California's Sierra Nevada to identify ROS occurrences and their connection with ARs during the 1998–2014 winters. Out of the 54 ROS dates identified, 26 (i.e., 48%) are associated with ARs, which is 3 times the general AR frequency in precipitation days. Composite analysis shows that compared to ARs without ROS, ARs with ROS are on average warmer by ~2° K, with SWE loss of ~0.7 cm/day (providing 20% of the combined water available for runoff) and nearly 50% higher streamflow-precipitation ratios. The AIRS retrievals reveal distinct offshore characteristics of the two types of ARs. The results highlight the importance in observing these events for snow, rain, and flood prediction.

In the context of a comprehensive regional climate dynamic downscaling study conducted by four NASA centers (JPL, GSFC, ARC, MSFC), winter precipitation (PR) characteristics in western United States (WUS) related to atmospheric river (AR) landfalls were examined and used to evaluate model performance for three climatological

sub-regions in WUS, Pacific Northwest (PNW), Pacific Southwest (PSW) and Great Basin (GB)(Kim, et al. 2017a). The regional model simulations included NASA's NU-WRF run at three resolutions and with and without spectral nudging. All simulations reasonably represent these observed variations in the AR-related winter PR fractions and the daily PR PDFs according to AR landfall locations. However, unlike for the entire winter period, no systematic effects of resolution and/or spectral nudging are identified in simulating these AR-related PR characteristics. Dynamical downscaling in this study generally yield positive added values to the MERRA2 PR in the AR-related PR.

Water – Ecosystem/Vegetation

WEC seeks to understand the two-way interactions between the hydrosphere and ecosphere. The availability of water for life encompasses the water supply, which includes the timing, magnitude, duration, and storage capabilities of the water (groundwater, soil moisture, surface water, snow, ice melt), as well as the water quality and the influence of water on the geomorphology. Ecosystems are a living water reservoir and contribute to moving water through the global water and energy cycles through evapotranspiration. Furthermore, anthropogenic activities such as agriculture production contribute to the global water budget and energy cycle. The three studies below are singled out as advancing our understanding about the water-ecosystem/agriculture interface. Additionally, Fisher et al. (2017) reviewed the current state of evapotranspiration remote sensing.

Employing multiple sources of data enables cross-disciplinary studies. One such study by A. et al. (2017) combined soil moisture (SM), terrestrial water storage (TWS), enhanced vegetation index (EVI), and solar-induced fluorescence (SiF) to investigate multiple aspects of the water cycle, as well as coupling points with the carbon cycle. They found that during nominal years the vegetation-moisture relationship follows the gradient of mean annual precipitation. Temporally, grassland, though susceptible to drought, is able to make a speedy recovery. Generally, near surface soil moisture is coupled with, and has similar characteristics time scales as TWS. However, during drier years TWS manifests stronger persistence, thus having a longer recovery period and potentially inducing a moisture constraint on vegetation growth. Zhao et al. (2017) presented a drought severity index (DSI) that monitors TWS changes from GRACE. This index has shown good agreement with existing monthly indices such as the Palmer Drought Severity Index and the normalized difference vegetation index. However, by use of GRACE, it incorporates the human impacts of groundwater withdrawal. The DSI could be a globally consistent and effective drought monitoring tool, particularly where sparse ground observations (especially precipitation) limit traditional methods of drought monitoring.

Madani et al. (2017) used satellite soil moisture and SiF observations, along with in situ observations, to investigate controls on Gross Primary Productivity. General results showed consistency with climate response characteristics indicated from sparse global tower observations while providing more extensive coverage for verifying and refining global carbon and climate model assumptions and predictions. They found that at global scales, ecosystem productivity is affected jointly by Vapor Pressure Deficit

(VPD), minimum daily air temperature, and soil moisture, with the three values individually significant over 60, 59, and 35 percent of the global domain, respectively. For arid ecosystems, the seasonal cycle of productivity was found to be influenced more by soil water content than VPD.

Multiple sources of satellite observations are extremely useful for large-scale crop monitoring and yield estimation, which is important for both scientific and practical applications. For this purpose, a new study by Guan, K., et al. (2017) investigated use of MODIS Enhanced Vegetation Index (EVI), estimated Gross Primary Production from GOME-2 SiF (SIF-GPP), thermal-based ALEXI Evapotranspiration (ET), QuikSCAT Ku-band radar backscatter, and AMSR-E X-band passive microwave Vegetation Optical Depth (VOD). Use of Partial Least Squares Regression for a period between 2007 and 2009 revealed that the first component, an integrated proxy of crop aboveground biomass, explained 82% of the variability of modelled crop yield and the second component, dominated by environmental stresses, explained 15% of the variability. For the first component, it was found that all observation techniques investigated provide similar information. However, when removing the common information across the observation types, EVI and SIF-GPP do not provide much additional information, though Ku-band backscatter, thermal-based ALEXI-ET and X-band VOD provide independent information on environmental stresses that improves overall crop yield predictive skill. In particular, Ku-band backscatter and associated differences between morning and afternoon overpasses contribute unique information on crop growth and environment stress.

Water Budget and water Cycle Dynamics

The bulk of WEC research activities focus on the characterization, quantification, and modeling of the different elements of the terrestrial water cycle: precipitation, snow, surface water, soil moisture, biological/ecosystem water, and groundwater. These activities include advancing science for our current missions (i.e. SMAP, GRACE, GPM, MODIS) and new research supporting missions that are either in development or in formulation (i.e. GRACE-FO, SWOT, NISAR). Several WEC funded activities came to fruition with an updated accounting of the global water and energy budgets leveraging many NASA investments to develop and produce individual variable data sets, from observations and reanalyses. Investments in these types of activities will enhance overall assessment through improved accounting of individual water budget/cycle terms. NASA is dedicated to global observations from spaceborne platforms, these investments align to support different stages of satellite mission development, data use, and societal benefit. This section outlines innovative research for select water budget/cycle elements where there was a concentration of published research.

Snow

Snow remains one of the significant challenges to remote sensing of the water cycle. Unlike other variables, a single remote sensing technique and/or wavelength of observation have proven insufficient to resolve Snow Water Equivalent (SWE) and other snow properties, especially at the high spatial scales (~100s of meter) that are necessary to investigate snow pack dynamics. With this, WEC continues to invest in a variety of research and technical approaches to better characterize snow. The Focus Area also

supported SnowEX, a large airborne and in situ data collection campaign that evaluated several different types of snow remote sensing techniques collected at the same time and location.

Li et al. (2017) demonstrated an improved accounting of SWE using AMSR-E 36.5 GHz passive microwave, coarse spatial scale (~10 km) measurements for the sparsely forested Upper Kern watershed (511 km^2) in the southern Sierra Nevada. Dry snow season (1 Dec – 28 Feb) observations were assimilated, using the Ensemble Batch Smoother (EnBS), into model predictions of SWE at 90-meter spatial resolution. Evaluated against snow courses and pillows, the EnBS SWE RMSE was 77.4 mm (13.1% relative to peak accumulation) despite deep snows (average peak SWE 545 mm). This is a marked improvement with a reduction in bias of 84.2% and RMSE by 35.4% over the unassimilated model prediction.

Leveraging the successful concept behind the Airborne Snow Observatory (ASO), Moller et al. (2017) investigated using Ka-band (8 mm wavelength) single-pass interferometric synthetic aperture radar (InSAR) for snow-depth mapping. Their approach would complement other remote sensing approaches because of its advantages as viable for a spaceborne mission that is capable of operating during cloud cover, day or night, and when the snow is wet, melting or very deep. Their study presents observations over the Tuolumne River Basin (in the Sierra Nevada Mountains of California) that are compared with the same day (April 24th, 2012) depth measurements of the scanning lidar of ASO. For this period, the snow surface was wet and melting, allowing for the disregard of the penetration of the electromagnetic waves into the snow volume. Over rugged terrain, heavy tree-cover, and low snow volumes, the depth maps had a standard deviation of less than one meter, with the largest differences occurring on slopes exceeding 40%. As these results were promising, the focus area invested in flying the Ka-band sensor again during the SnowEx field campaign of February 2017, which provided ASO observations along with in situ observations for more robust evaluation of the InSAR approach.

A proof-of-concept experiment was carried out by Shah et al. (2017) to demonstrate the feasibility of observing SWE using P-band signals of opportunity. The fundamental observation is the change in the phase of the reflected waveforms as related to the change in SWE. They used theoretical modeling to find that the change in SWE is approximately linearly dependent on the change in phase and verified by comparison with retrieved data from a tower-based experiment at Fraser, Colorado. Using a linear regression between measured phase and in situ SWE, they found a correlation of 0.94 and root mean square deviation of 7.5 mm. The correlation was found to be lower when compared with in situ snow depth, which agreed with the theoretical modeling. Overall, this is a very good agreement and shows that their proof-of-concept method has the potential to become an observation tool for snow monitoring since the approach could be extended to both airborne and spaceborne platforms.

Kumar et al. (2017) examine the limitation of using a single forcing dataset for specifying forcing uncertainty inputs for assimilation snow depth retrievals. Using an idealized data assimilation experiment, they demonstrate that the use of hybrid forcing input strategies (i.e. use of an ensemble of forcing products or through the added use of the forcing climatology) provides a better characterization of the background model error, which leads to improved data assimilation results, especially during the snow

accumulation and melt-time periods. They employ hybrid forcing ensembles for assimilating snow depth retrievals from the AMSR2 instrument over two domains in the continental U.S. with different snow evolution characteristics. Over a region near the Great Lakes, where snow evolution tends to be ephemeral, the hybrid forcing ensembles provide significant improvement relative to the use of a single forcing dataset. Over the Colorado headwaters, characterized by large snow accumulation, the impact of using the forcing ensemble is less prominent and is largely limited to the snow transition time periods.

SnowEx (https://snow.nasa.gov/snowex) is a multi-year airborne snow campaign with a focus on testing new approaches for mapping snow water equivalent in forested regions and other areas. WEC supported a three-week field campaign in February 2017 to evaluate a variety of different remote sensing techniques in a range of forested environments. The Snow Remote Sensing community met in March 2016 and provided site recommendations that led to the Grand Mesa in Colorado as the primary study area for SnowEx, and complemented it by using nearby Senator Beck Basin as a secondary site to provide a high mountain snow environment. Multiple aircraft flew, hosting a variety of payloads, including UAVSAR (L-band radar), Glisten-A (Ka-band radar), Airborne Snow Observatory (Lidar and imaging spectrometer), Cloud Absorption Radiometer (CAR), SnowSAR (X- and Ku-band SAR), and a Thermal IR video suite. NASA's ESTO-funded Wideband Instrument for Snow Measurements (WISM), which consists of a radiometer (8-40 GHz) and radar (X and Ku-band), was flown during week one for instrument evaluation. Numerous ground-based remote sensing instruments were installed at a local area site. In total, over 100 community scientists (many early career) participated in the field campaign and all received sampling and safety training. Numerous other agencies were partners on the project, with campaign leaders coming from the U.S. Forest Service and the U.S. Army Corp's Cold Regions Research Lab. In total, over 160 transects were successfully sampled and over 150 snow pits dug. Preliminary data, along with a list of all expected data sets, are currently available at https://snow.nasa.gov/snowex/preliminary-results, and will later be transferred to the NASA Snow and Ice Data Center (NSIDC). Under ROSES 2017, NASA/THP solicited for three year projects to use these data for snow remote sensing and scientific research.

Surface water

The focus area has made investments to improve our ability to resolve surface water and assess river discharge. Both are important advances to pursue and to stay current with the advances in land modeling efforts that have moved from a traditional climate paradigm, which disregards horizontal movement of water, to one that models surface processes more comprehensively and at higher spatial resolutions. This advancement can facilitate the use of WEC observations to support carbon cycle research that focuses on resolving roles of surface water and rivers in the carbon budget.

Nghiem et al. (2017) present an emerging technique to use Global Navigation Satellite System Reflectometery (GNSS-R) to delineate and assess surface water in wetlands. They found that recent GNSS-R signatures from aircraft over the Ebro River Delta in Spain and satellite measurements over the Mississippi River and adjacent watersheds can identify inundated wetlands under different vegetation conditions, including dense rice canopies and thick forest with tall trees, which are areas where

optical sensors and monostatic radar would be limited. Their approach should be adaptable to be used with CYGNSS for ~6 hourly repeat observations on the order of 1x7km resolution, albeit restricted to a latitudinal belt between 35°degrees North and South. Full exploitation of GNSS-R synergy, employing multiple satellite platforms, should facilitate study of methane pathways, including diffusion, aerenchyma, and ebullition, through the full seasonal cycle and especially during extreme events.

In preparation for the SWOT mission, NASA field tested the AirSWOT airborne simulator by flying it over the Tanana River in Alaska. Altenau et al. (2017) evaluated river slope and water surface elevation (WSE) derived from the instrument's observations. They found when comparing with in situ measurements along the river that the root-mean-square error is 9.0 cm for WSEs averaged over 1 km^2 areas and 1.0cm/km for slopes along 10 km reaches. These results indicated that the instrument is capable of resolving spatial variations in slope critical for characterizing reach-scale hydraulics, making the instrument valuable for validating future SWOT measurements as well as hydrologic analysis and flood modeling studies.

Soil moisture

Soil moisture is the vital connector between surface water and groundwater; it is also the interface between water and plants for many ecosystems. Soil moisture influences precipitation runoff, snowmelt volumes, and many fluvial hazards. The Decadal Survey identified SMAP as a high priority to address this measurement need. Since its launch, NASA and the focus area have put a high priority on evaluating SMAP data. The three studies below look at SMAP science and its data products, along with a study using MODIS potential evapotranspiration products in a soil moisture model.

Piepmeier et al. (2017) evaluated the first year on-orbit performance of SMAP's conical scanning L-band microwave radiometer, designed to measure soil moisture with 4% volumetric accuracy at 40-km spatial resolution. Their analyses indicate that the electrical and thermal characteristics of the electronics and internal calibration sources are very stable and promote excellent gain stability. The gain spectrum exhibits low noise at frequencies >1 MHz and 1/f noise rising at longer time scales fully captured by the internal calibration scheme. Results from sky observations and global swath imagery of all four Stokes antenna temperatures indicate that the instrument is operating as expected.

The SMAP radiometer is used to create a level 2 soil moisture product (L2_SM_P) posted on a 36-km Earth-fixed grid using brightness temperature observations from descending passes. Burgin et al. (2017) provide the first comparison of the validated-release L2_SM_P product with soil moisture products of the Soil Moisture and Ocean Salinity (SMOS), Aquarius, Advanced Scatterometer (ASCAT) and Advanced Microwave Scanning Radiometer 2 (AMSR2) missions. The first two missions operate in the L-band, with the latter two using C-band (~5-6GHz) to derive their soil moisture products. SMAP and SMOS appear most similar of the five soil moisture products considered, overall exhibiting the smallest unbiased root-mean-square difference and highest correlation. Overall, SMOS tends to be slightly wetter than SMAP, excluding forests where some differences are observed. SMAP and Aquarius

compare well, albeit it for only a two month overlap period, especially over low to moderately vegetated areas. SMAP and ASCAT show similar overall trends and spatial patterns, with ASCAT providing wetter soil moisture than SMAP over moderate to dense vegetation. SMAP and AMSR2 largely disagree in their soil moisture trends and spatial patterns; AMSR2 exhibits an overall dry bias, while desert areas are observed to be wetter than with SMAP.

Although the SMAP radar only operated in data collection mode from mid-April to early July 2015, it is important to assess its abilities to inform future plans for satellite soil moisture observations. Kim et al. (2017b) inverted physically based forward models of radar scattering for individual vegetation types using a time-series approach to retrieve soil moisture, while correcting for the effects of static roughness and dynamic vegetation. Compared with past studies in homogeneous field scales, this performed a stringent test with the satellite data in the presence of terrain slope, subpixel heterogeneity, and vegetation growth. These retrievals were assessed at 14 core validation sites representing a range of global soil and vegetation conditions over grass, pasture, shrub, woody savannah, and corn, wheat, and soybean fields. The predictions of the forward models used agree with SMAP measurements to within 05 dB unbiased root-mean-square error (ubRMSE) and -0.05 dB (bias) for both copolarizations. Soil moisture retrievals had an accuracy of 0.052 m^3/m^3 ubRMSE, -0.015 m^3/m^3 bias, and a correlation of 0.50, when compared to in situ measurements. The successful retrieval demonstrates the feasibility of a physically based time series retrieval with L-band SAR data for characterizing soil moisture over diverse conditions of soil moisture, surface roughness, and vegetation.

Bowman et al. (2017) evaluated MODIS-derived potential evapotranspiration (M-PET) for input into the Sacramento Soil Moisture Accounting (SAC-SMA) model by comparing streamflow simulations with existing SAC-SMA methods, for basins in NOAA's North Central River Forecast region. Results were mixed, with the model showing improvement in four of fifteen basins; however, in additional cases, there were promising results suggesting that the time-varying M-PET input may produce a more physically realistic representation of evapotranspiration process in both the lumped and distributed version of the SAC-SMA model.

Groundwater

Measuring groundwater is challenging in localized basins, let alone on global scales. There are currently two approaches for measuring and tracking changes in groundwater. Interferometric Synthetic Aperture Radar measures the surface deformation associated with the natural anthropogenic withdrawal and recharge/injection of water. Water volume is then obtained by modeling the surface deformation. GRACE (and the anticipated launch in 2018 of GRACE-FO) provides global measurements of mass change, including the redistribution of water (solid and liquid). Both techniques measure changes in water in storage and not the absolute volume. The studies summarized below analyze changes in groundwater.

Smith et al. (2017) mapped regions in the San Joaquin Valley (California), where inelastic deformation/subsidence associated with over drafting occurred during the study period, June 2007 to December 2010. They estimated the amount of permanent aquifer system compaction by incorporating multiple data sets: the total deformation derived from InSAR and the skeletal-specific storage and hydraulic parameters were estimated

from geologic information and measured water levels. They used two approached, one they considered to provide an estimate of the lowest possible amount of inelastic deformation, and one that provided a more reasonable estimate. These two methods, respectively, estimated a permanent loss of 4.1E8 m^3 and 7.5E8 m^3 groundwater storage, values which correspond to 5% and 9% of the volume of groundwater used over the study period.

Although powerful, assimilation of satellite data is not without its problems, as pointed out by Girotto et al. (2017). The study investigated some of the benefits and drawbacks of assimilating terrestrial water storage (TWS) observations from GRACE into a land surface model over India. They found that assimilation of GRACE TWS into land surface models can introduce (correct) long-term trends and improve interannual variability of groundwater. They also found that an inaccurate negative trend in simulated evapotranspiration can occur in part because the model is not able to represent anthropogenic groundwater withdrawals. This is because groundwater withdrawal is for agriculture purposes and is maintaining (if not enhancing) evapotranspiration. The assimilation also reveals a problem -- that the model is not able to resolve depth dependent process between shallow versus deeper groundwater stores. Furthermore, the study's results emphasize the importance of representing anthropogenic processes in land surface modeling and data assimilation systems.

Scientists at NASA GISS and the University College London provided in Dalin et al. (2017) the first quantification of depleting groundwater embedded in the world's food trade by combining unique global, crop-specific estimates of nonrenewable groundwater abstraction with international food trade data. They found that approximately eleven percent of non-renewable groundwater used for irrigation is embedded in food trade, of which two-thirds is exported by Pakistan, the United States, and India alone. This quantification is based on a combination of global, crop-specific estimates of non-renewable groundwater abstraction and international food trade data. The scientists used a global hydrological and water resources model to simulate crop water use for 26 irrigated crop types, validated with groundwater data, country statistics, and NASA's GRACE satellite observations. A vast majority of the world's population lives in countries sourcing nearly all their staple crop imports from partners who deplete groundwater to produce these crops, highlighting risks for global food and water security. Some countries, such as the U.S., Mexico, Iran, and China, are particularly exposed to these risks because they both produce and import food irrigated from rapidly depleting aquifers. This study can help improve the sustainability of global food production and groundwater resources management by identifying priority regions and agricultural products at risk, as well as their end-consumers.

Multi-parameter

The WEC focus area seeks to enhance our understanding of the transfer and storage of water and energy in the Earth system and assess the relationships of multiple water budget parameters. McColl et al. (2017) begins to quantify the relationship of soil moisture with surface water and groundwater. They found that surface soil moisture, estimated to make up less than 0.001% of global freshwater, retains a median 14% of precipitation falling on land after three days. The retained fraction of surface soil moisture storage is highest over arid regions and in regions where drainage to

groundwater storage is lowest. They concluded that lower groundwater storage in these regions may be due not only to lower precipitation, but the complex partitioning of water by the surface soil moisture storage layer. Their results are also consistent with recent findings that found significant positive soil moisture –precipitation feedbacks in the Western U.S., where they demonstrated that surface soil retention of precipitation is higher than the global average. These results provide a useful new test of model fidelity of the global water cycle dynamics, as those land models with a surface soil moisture layer can generate a stored precipitation fraction that can be evaluated with SMAP data.

Water quality

Remote sensing of the quality of water is important not just to address society's water availability problems, but it is also inter-connected with many different components of the Earth system. Until recently, too few optical observations have been made to develop and validate visible spectral satellite remote sensing products of Lake Superior. Mouw et al. (2017) describe coincidently observed inherent and apparent optical properties, such as absorption, scattering, backscattering, attenuation, chlorophyll concentration and suspended particulate matter, along with biogeochemical parameters over the ice-free months of 2013-2016. The data substantially increased the optical knowledge, allowing for visible spectral satellite algorithm development and characterization of the variable light field, particle, phytoplankton, and colored dissolved organic matter distributions, helpful in food web and carbon cycle investigations.

Particulate inorganic matter (PIM) is a key component in estuarine and coastal systems, and plays a critical role in trace metal cycling. To improve understanding of coastal dynamics and biogeochemistry, Zhang et al. (2017) improved quantification of PIM in terms of its concentration, size distribution, and mineral species composition. The angular pattern of light scattering contains detailed information about the size and composition of the particles. These volume scattering functions (VSFs) were measured in Mobile Bay, Alabama. From measured VSFs, they determined through inversion the particle size distributions (PSDs) of major components of PIM, amorphous silica and clay minerals. An innovation here is the extension of our reported PSDs significantly into the sub-micro range. The PSDs of autochthonous amorphous silica exhibit two unique features: a peak centered at about 0.8 um between 0.2 and 4 um and very broad shoulder, essentially extending from 4 um to >100 um. With an effective and steady particle source from blooming diatoms, the shapes of amorphous silica PSDs for sizes <10 um varied little across the study area, but showed more particles sizes of >10 um inside the bay, likely due to wind-induced resuspension of larger frustules that have settled. Ultimately, the derived PSDs also indicated a very dynamic situation in Mobile Bay when a cold weather front passed through during the experiment. When the northerly winds have speeds up to 15 m/s, both amorphous silica and clay mineral showed a dramatic increase in concentration and broadening in size distribution outside the exit of the barrier islands, indicative of wind-induced resuspension and subsequent advection of particles out of Mobile Bay. Results of the study also demonstrate the potential of applying VSF-inversion in studying biogeochemistry in the estuarine-coastal ocean system.

The California Harmful Algae Risk Mapping (C-HARM) system, described in Anderson et al. (2016), was recently developed to predict the spatial likelihood of blooms

and dangerous levels of domoic acid (DA) using a unique blend of numerical models, ecological forecast models of the target group, Pseudo-nitzschia, and satellite ocean color imagery. Daily predictions of biogeochemical parameters are routinely generated at the Central and Northern California Ocean Observing System (CeNCOOS) and posted on its public website (http://www.cencoos.org). The skill assessment of the model output of the nowcast data is restricted to nearshore pixels that overlap with routine pier monitoring of HABs in California during 2014-2015. Model lead times are found to best correlate with DA measured with solid phase adsorption toxin tracking and marine mammal strandings from DA toxicosis, suggesting long-term benefits of the HAB predictions.

Airborne hyperspectral observations of HABs hold promise to distinguish potential HABs from nuisance blooms, determine their concentrations, and delineate their movement in an augmented spatial and temporal resolution and under clouds. In 2014, a HAB in Lake Erie reached severe levels and threatened Ohio drinking water. Since then, NASA Glenn Research Center has taken airborne hyperspectral observations of Lake Erie and confirmed HABs. Collected data from the airborne flights is processed, user accessible products are generated, and then distributed to shoreline water resource managers. The project and its data helped state and municipal authorities realize the potential extent of a bloom threatening the Cincinnati water supply, and triggered response sampling, even before the visual river-wide scums started to form. NASA Technical Report (NASA/TM-2017-219071) is a comprehensive 78-page report by Lekki et al (2017) that describes the end-to-end process for airborne HAB assessment from the airborne data collection to the conversion of the raw remote sensing data to information products, including system calibration and validation, atmospheric correction, and improvement of the algorithms that produce the data products. Furthermore, the report explores several strategies for atmospheric correction of the HSI2 data, of which the most positive results were obtained from several vicarious calibration methods, such as the empirical line method and the empirical mirror-based calibration method. Finally, the team plans to further publish their airborne remote sensing techniques to improve the monitoring and understanding of algal blooms in complex inland and coastal waters.

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FY 2017 Annual Performance Indicator	FY 14	FY15	FY16	FY17
ES-17-7: 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-17-9</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.

The NASA Climate Variability and Change (CVC) focus area (https://science.nasa.gov/earth-science/focus-areas/climate-variability-and-change) continues to increase our knowledge of global climate and sea level on seasonal to decadal time scales. Through a wide range of interdisciplinary research, it supports the collection and assessment of satellite, aircraft and ground-based observations of sea ice, glaciers, ice sheets and the global ocean, and their integration into comprehensive, interactive Earth system models. Highlights of research conducted in the past year are summarized below.

Sea Ice in the Earth System

Sea ice plays a critical role in the Earth system by reflecting incident sunlight, and regulating the transfer of heat and momentum between the atmosphere and ocean. In addition to characterizing the extent, concentration, thickness and dynamics of sea ice in both hemispheres, research in the past year continued to investigate the processes that govern its seasonal and long-term evolution.

Characterizing sea ice

The rapid loss of Arctic sea ice continued this past year, reaching its minimum extent for 2016 on September 10, at 4.14 million square kilometers (1.60 million square miles). This ties the 2007 minimum as the second-lowest extent in the passive-microwave (PMW) satellite record, and reinforces the long-term downward trend in Arctic ice extent (-13.3% per decade). The ten lowest September sea ice extents in the satellite record have all occurred in the last ten years. (http://nsidc.org/arcticseaicenews/2016/09/)

After four years of record or near-record maximum extents, sea ice around Antarctica plummeted to its lowest minimum extent in the satellite record on March 3, 2017, at 2.11 million square kilometers (815,000 square miles). This reflected especially low sea ice extent along the coast of West Antarctica, particularly in the Amundsen and Ross Seas. The previous record-low minimum extent occurred in February 1997. (http://nsidc.org/arcticseaicenews/2017/03/)

Quantifying connections between sea ice and the ocean and atmosphere

Two strong cyclones passed through the Chukchi Sea in August 2016, likely contributing to the observed acceleration of ice loss in the Arctic just prior to the September minimum. The role of such storms has been the focus of increasing study in recent years. **Boisvert et al. (2016)**, for example, used data from the Atmospheric Infrared Sounder

(AIRS) onboard the Aqua satellite, to examine the impact of a large Arctic cyclone in December 2015 in the Barents and Kara Seas. They found that the anomalously warm air mass transported by this storm produced significant, localized melt of sea ice, and a dynamical retreat of the ice edge.

The variability of sea ice extent in the South Pacific has been associated with the atmospheric anomalies linked to the Southern Oscillation (SO) – the seesaw in sea level pressure between the southeastern Pacific and the Indian Ocean-Australian region. **Kwok et al. (2016)** found a strong correlation between the Southern Oscillation Index (SOI) and the ice edge delineated in the passive-microwave satellite record from 1982 to 2013. Their analysis suggests that the SO contributes not only to the wind anomalies that drive the variability of local ice drift and ice edge, but also to their time trends.

With the National Science Foundation, the CVC focus area co-sponsored a workshop by the National Academies of Sciences, Engineering, and Medicine (NASEM), in Boulder, Colorado, to further explore potential mechanisms driving the evolution of recent Antarctic sea ice variability and to discuss ways to advance understanding of Antarctic sea ice and its relationship to the broader ocean-climate system. The proceedings of the workshop highlighted the need to ensure long-term records of sea ice extent, obtain oceanographic measurements, develop improved model parameterizations, and communicate Antarctic sea ice trends more clearly to the public **(NASEM, 2017)**.

Validating and improving models of sea ice cover

Although previous studies established a strong correlation between spring Arctic sea ice-ocean conditions and the September sea ice extent (SIE), they did not succeed in producing accurate seasonal forecasts. **Petty et al. (2017)** used PMW-derived sea ice concentration (SIC) and melt onset (MO) to produce skillful forecasts of the SIE. The 2017 forecasts are being generated and disseminated to the community in near real-time.

Accurate simulation of sea-ice mass balance requires a realistic representation of sea-ice deformation in models. **Spreen et al. (2017)** compared simulations of sea-ice deformation from numerical models to synthetic aperture radar (SAR) satellite observations from 1996 through 2008. They found that the mean sea-ice deformation rate is about 40% lower in the model solutions than in the satellite observations, especially in the seasonal sea-ice zone.

Land Ice Processes and Sea Level Change

The ice sheets of Greenland and Antarctica, as well as the worldwide inventory of small glaciers and ice caps, make substantial contributions to global sea level. These contributions are governed by a variety of processes, including surface mass balance, interactions between the ice and the ocean, and meltwater transport on and within the ice. These studies have employed a variety of techniques to assess the changes being observed, and to improve understanding and modeling of these processes.

Characterizing land ice properties

The basal thermal state of an ice sheet (frozen or thawed) is an important control upon its evolution, dynamics, and response to external forcings. **Macgregor et al. (2016)** synthesized outputs from ice-flow models, radiostratigraphy, surface velocity, and Moderate Resolution Imaging Spectroradiometer (MODIS) imagery, to constrain the basal thermal state of the Greenland Ice Sheet (GrIS). The modeling outputs and remote-sensing data generally agree that the Northeast Greenland Ice Stream and large portions of the southwestern ice-drainage systems are thawed at the bed, whereas the bed beneath the central ice divides, particularly their west facing slopes, is frozen.

Combining bathymetry from the Oceans Melting Greenland (OMG) mission with observations of ice velocity and thickness, **Morlighem et al. (2016)** produced estimates of bed depth and ice thickness across the ice-ocean boundary with unprecedented accuracy. Results along the northwest coast of Greenland reveal complex structural features such as valleys, ridges, bumps, and hollows, which have important implications for channeling ice flow toward the continental margin, and for controlling the amount of warm, salty Atlantic Water reaching the glaciers.

Mouginot et al. (2017) developed a method to process Sentinel-1 and RADARSAT-2 synthetic aperture radar (SAR) and Landsat-8 optical data in a synergistic fashion and automatically calibrate, mosaic, and integrate these data sets together into seamless, ice-sheet-wide products. Using all available data in each year, they produced annual mosaics of ice motion in Antarctica and Greenland. The resulting pool of remote sensing products is a significant advance for observing changes in ice dynamics over the entire ice sheets and their contribution to sea level.

Determining mass balance and contributions to sea level

Nilsson et al. (2016) developed a new processing method that improved CryoSat-2 tracking of the snow/ice surface, with lower sensitivity to changes in near-surface dielectric properties. For data collected in interferometric synthetic aperture mode, over the high-relief regions of the Greenland Ice Sheet, they found an improvement in the root-mean-square error (RMSE) of 27 and 40 % compared to ESA's L2 Baseline-B product in the derived elevation and elevation changes, respectively. In the interior of the ice sheet, where CryoSat-2 operates in low-resolution mode, they found an improvement in the RMSE of 68 and 55 % in the derived elevation and elevation changes, respectively. This produced a total volume loss of 289 ± 20 cubic km per year, nearly 65 cubic km per year greater than the loss determined from the ESA L2 product.

Melting of the Greenland ice sheet (GrIS) and its peripheral glaciers and ice caps (GICs) contributes about 43% of contemporary sea level rise. **Noël et al. (2017)** used a novel, 1 km surface mass balance product, evaluated against in situ and remote sensing data, to identify 1997 (± 5 years) as a tipping point for the mass balance of the GICs. That year marks the onset of a rapid deterioration in the capacity of the GICs firn to refreeze

meltwater, evidenced by an increase in runoff relative to meltwater production, in sharp contrast to the GrIS, which retains most of its refreezing capacity for now.

Over the last two decades, the glaciers and ice caps in Queen Elizabeth Islands (QEI), Canada have experienced an increase in ice mass loss. **Millan et al. (2017)** combined satellite-derived ice velocity data from 1991 to 2015 with ice thickness data from Operation IceBridge to calculate ice discharge. During 1991–2005, they found that 52% of the QEI mass loss was from ice discharge, with the remaining 48% from surface mass balance (SMB). This changed dramatically in the 2005–2014 interval, with 90% of the mass loss stemming from SMB, and only 10% due to ice discharge. Currently, SMB processes dominate QEI mass balance, with ice dynamics playing a significant role only in a few basins.

Examining the role of sub- and supraglacial water in ice sheet dynamics

Poinar et al. (2017) investigated the plausibility of firn-aquifer water draining to the bed through crevasses using airborne and satellite data in conjunction with a crevasse propagation model. They found that crevasses receiving firn-aquifer model fracture through to the bed, ~1000 m below, in 10–40 days. Refreezing of the water within the ice raises the average local ice temperature by ~4°C, over a ten-year period, which enhances deformational ice motion. In the absence of an aquifer, they found that no surface melt would reach the bed; instead it would refreeze within the ice. They advocate that the aquifer and crevasses should be viewed as a common system, which may uniquely affect ice-sheet dynamics by routing a large volume of water to the bed outside of the typical runoff period.

Combining surface elevation, ice thickness and ice speed data, **Smith et al. (2017)** uncovered a system of subglacial lakes that drained between June 2013 and January 2014 under the central part of Thwaites Glacier, West Antarctica. Much of the drainage happened in less than 6 months, with an apparent connection between three lakes spanning more than 130 km. The observed motion of the water, however, suggests that it can move against the apparent potential gradient, at least during lake-drainage events – revealing an important limitation in the ability of hydro-potential maps to predict subglacial water flow. Nonetheless, they found that the added water appears to have had no substantial effect on the ice speed, in contrast to what has been reported for some other glaciers.

Joughin et al. (2016) used WorldView, IceBridge, and TerraSAR-X data to reveal significant variability in the degree to which Pine Island Glacier's ice shelf is grounded, much of which is caused by deep ice keels that scrape along the sea floor. These data also reveal drainages of sub-glacial lakes with little coincident change in speed, contrary to earlier results that showed speedup during such events. The TerraSAR-X analysis demonstrates how important time series of ice motion data are, such as those which NISAR will provide.

Bell et al. (2017) identified persistent active drainage networks – interconnected streams, ponds and rivers – on the Nansen Ice Shelf in Antarctica, that export a large fraction of the ice shelf's meltwater into the ocean, potentially reducing the likelihood of collapse. During warmer melt seasons, these drainage networks remain active for longer and export more water. Similar networks are present on the ice shelf in front of Petermann Glacier, Greenland, but other systems, such as on the Larsen C and Amery Ice Shelves, currently retain surface water. Their results suggest that, in a future warming climate, surface rivers could export meltwater off the large ice shelves surrounding Antarctica, contrary to present ice-sheet models, which assume that meltwater is stored on the ice surface, where it triggers ice-shelf disintegration.

Quantifying connections between land ice and the ocean and atmosphere

Mass loss within individual outlet glacier catchments in Greenland exhibits unexplained heterogeneity, hindering projections of ice-sheet response to future environmental forcing. **Felikson et al. (2017)** used digital elevation model differencing to resolve the dynamic portion of surface elevation change from 1985 to present within 16 outlet glacier catchments in West Greenland. They found that the extent of thinning and, thus, mass loss, is limited by glacier geometry, and furthermore, that 94% of the total dynamic loss occurs between the terminus and the location where the speed of a kinematic wave of thinning is at least three times larger than its diffusive speed. This empirical threshold enables the identification of glaciers that are not currently thinning but are most susceptible to future thinning.

Snow accumulation is the largest component of the ice sheet's surface mass balance, but in situ observations are inherently sparse, and models are difficult to evaluate at large scales. **Koenig et al. (2016)** quantified recent Greenland accumulation rates using ultra-wideband (2–6.5 GHz) airborne snow radar data collected as part of Operation IceBridge between 2009 and 2012. They used a semi-automated method to trace the radiostratigraphy and derive annual net accumulation rates. Comparisons with contemporaneous ice cores show that snow radar captures both the annual and long-term mean accumulation rate accurately. Outputs from a regional climate model (MAR) match the radar-derived accumulation rates in the ice sheet interior, but produce higher values over southeastern Greenland.

Pine Island Glacier (PIG) remains a key focus for the study of ice-ocean interactions in Antarctica. **Jeong et al. (2016)** reported on the recent development of multiple rifts initiating from basal crevasses in the center of the PIG ice shelf, resulted in calving farther upglacier than previously observed. Examination of ice velocity suggests that this internal rifting resulted from the combination of a change in ice shelf stress regime caused by disintegration of ice mélange and intensified melting within basal crevasses, both of which may be linked to ocean forcing.

Christianson et al. (2016) combined glaciological and oceanographic data to produce a consistent picture of ocean forcing and glacier response at PIG. They conclude that ongoing glacier retreat and accelerated ice flow were likely triggered a few decades ago

by increased ocean-induced thinning, which may have initiated marine ice sheet instability. Despite a 60% drop in ocean heat content over a two-year period, the basin-wide thinning signal did not change, suggesting that, as predicted by theory, once marine ice sheet instability is underway, a single transient high-amplitude ocean cooling has only a relatively minor effect on ice flow.

Validating and improving models of land-based ice and contributions to sea level

Price at al. (2016) developed a new ice sheet model validation framework – the Cryospheric Model Comparison Tool (CmCt) – that takes advantage of ice sheet altimetry and gravimetry observations collected over the past several decades and applies it to modeling of the Greenland ice sheet. They evaluated model outputs against the observations and found that gravimetry – unlike altimetry – was able to unambiguously distinguish between simulations of varying complexity. The CmCt was able to provide a quantitative score for assessing a particular model and/or simulation, confirming that dynamic ice sheet models, when appropriately initialized and forced with the right boundary conditions, demonstrate a predictive skill with respect to observed dynamic changes that have occurred on Greenland over the past few decades.

The mechanisms causing widespread flow acceleration of Jakobshavn Isbræ, West Greenland, remain unclear despite an abundance of observations and modeling studies. **Bondzio et al. (2017)** simulated the glacier's evolution from 1985 to 2016 using the Ice Sheet System Model. They explored the inland propagation of thinning along the glacier, and demonstrated how one process – shear margin weakening – is the likely cause. The underlying mechanisms are likely to apply to many other marine-terminating outlet glaciers in Greenland, and the interplay of calving front migration, shear margins, and the thermal regime is important to account for in projections of future sea level rise.

Reducing the uncertainty in the past, present, and future contribution of ice sheets to sea-level change requires a coordinated effort between the climate and glaciology communities. Over the last year, NASA continued to provide support for the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6), which provides a basis for investigating the feedbacks, impacts, and sea-level changes associated with dynamic ice sheets and for quantifying the uncertainty in ice-sheet-sourced global sea-level change. **Nowicki et al. (2016)** report on the experimental design for ISMIP6, which relies on CMIP6 climate models and includes, for the first time within CMIP, coupled ice-sheet–climate models as well as standalone ice-sheet models.

Ocean-Atmosphere Interactions

The ocean's interaction with the overlying atmosphere has strong implications for weather, climate, energy and carbon budgets. Atmosphere and ocean interact on various temporal scales, from hours to months to decades. Examples include the influence of sea surface temperature on hurricane tracks, the influence of ocean temperature on its ability

to take up carbon, and winds affecting ocean circulation. It is hence of high importance to understand these interactions and short- and long-term impacts.

Novel surface wind estimates using SMAP observations

The Soil Moisture Active/Passive (SMAP) mission was primarily designed to measure and quantify soil moisture over the continents to better understand the links between Earth's water, energy and carbon cycles and enhance our ability to monitor and predict natural hazards like floods and droughts. A new investigation by **Yueh at al. (2016)** shows that SMAP data can also be utilized to monitor ocean winds. The near-surface ocean wind is a driving force in air-sea interaction process and is a key component in skillful forecasts of tropical cyclone track and intensity, thus requiring accurate direct observations of the surface wind field. However, traditional spaceborne radiometers and scatterometers, operating at C- to Ka-band frequencies, have limited sensitivity to strong hurricane winds. In their study, Yueh et al. (2016) demonstrate the advantage of using L-band microwave wind radiometers from SMAP in filling in a critical gap for surface observations during severe weather. A related study by **Fore et al. (2016)** further examines the accuracy of the derived SMAP wind products using a radar-only and combined active/passive algorithms. Their analysis suggests that SMAP wind vectors performance is superior to traditional scatterometers for high-wind conditions (>12.5 m/s), which has the potential to open new frontiers in marine hazard avoidance.

Toward better characterization of ENSO events

While the El Nino Southern Oscillation (ENSO) has strong impacts on Earth's water and carbon cycle, coastal ocean environments and weather patterns, some mechanisms and forcing still require a better understanding to improve our understanding of its local and global impact.

Hu and Fedorov (2017) found a connection between the frequency of El Nino events and its influence on global mean surface temperatures. They suggest that ENSO events control inter-annual variations in atmospheric heating rate in the tropics, emphasizing the importance of ocean heat uptake for interpreting global temperature curves. Their analysis explains, for example, the continuing global warming trend and rapid temperature rise, associated with atmospheric heat release that accompanied ENSO conditions during 2014-2016. Alternatively, weak ENSO activity can lead to slower rates of increase in global surface temperatures, such as those observed in the mid-2000s and dubbed "global warming hiatus."

Previous studies have shown that nonseasonal variations in global-mean sea level (GMSL) are significantly correlated with ENSO. **Piecuch and Quinn (2016)** diagnosed the GMSL budget for ENSO events, using data from Argo profiling floats, satellite gravimetry data from GRACE, and radar altimetry during 2005–2015. They demonstrated that steric (density) and barystatic (mass) effects make comparable contributions to the GMSL budget during ENSO, in contrast to previous interpretations,

based largely on hydrological models, which emphasized the barystatic component. The steric contributions reflect changes in global ocean heat content, centered on the Pacific Ocean. These results have implications for interpreting the "surface warming slowdown" in the early 2000s, and for constraining Earth's radiation balance and hydrological cycle.

Hydrology-Ocean Interactions

The ocean plays a strong role in the global water cycle. Water is transported between the continents and ocean via evaporation, winds, precipitation, and runoff. This balance has implications for water resources, infrastructure, and sea levels on a variety of temporal and spatial scales. In recent years, significant progress has been made in understanding this global exchange.

Better understanding of the water cycle by multi-sensor analysis

With the launch of missions that can measure surface salinity (Aquarius, SMAP), significant progress is being made in understanding the connection between precipitation, evaporation, ocean winds and circulation. Recent studies utilized salinity data to gain improved insights into the global ocean water cycle and particularly address whether the water cycle shows signs of intensification, which has potential impacts on weather patterns over the continents, including potential for increased flood or drought.

A new study by **Vinogradova and Ponte (2017)** reveals a general tendency of drying of arid subtropical ocean regions and wetting in the tropical and mid-to-high latitudes over the past two decades. Since 1992, the global average amplification of the ocean water cycle is 2-5%, depending on the product chosen, which is generally consistent with that predicted by thermodynamics and the Clausius-Clapeyron relation of 7.6%-per-degree of warming. The differences in estimates of freshwater fluxes is further discussed by **Yu et al. (2017)**, who suggest potential sources for the observed discrepancies among various satellite-derived products using a variety of metrics.

The changes in the amount of freshwater leaving and entering the oceans via the processes of evaporation, precipitation, and runoff (the ocean water cycle) are expected to leave "fingerprints" detectable in other ocean variables, such as ocean salinity. Although a direct link between the changes in surface salinity and changes in freshwater fluxes is rather difficult to observe on timescales relevant to the observations coverage, the consensus of the research community outlined in **Durack et al. (2016)** is that ocean salinity can be effectively used as an implicit, rather than explicit, indicator for changes in the water cycle.

Salinity measurements have also proven to be useful for anticipating extreme rainfall events on land. That is, all rainfall originates from the ocean and when it more water evaporates than usual it leaves a positive salinity anomaly. Similarly, less export of water from the ocean leaves a fresh anomaly. The record of salinity anomalies relative to climatology is a valuable predictor of rainfall anomalies elsewhere in the climate system, including on land. Li, Schmitt and Ummenhofer (2017) documented how extra water exported from the western North Atlantic is clearly responsible for flood events in the US

Midwest. The significant spring time surface salinity anomalies are an excellent predictor of summertime rainfall, providing much much improved seasonal forecasts over conventional methods such as SST or ENSO.

Understanding salinity measurements

Salinity measurements are essential to understand the global water cycle as well as short- and long-term variability in ocean circulation. Since satellite salinity measurements have only been available starting in the last decade, continuous improvements in understanding these measurements are made by using ancillary datasets.

New studies by **Meissner et al. (2016)** found ways to improve salinity data products using sea surface temperature data and finding connections between satellite surface salinity and near-surface oceanic properties. The latter is further elaborated in a community paper by **Boutin et al. (2016),** who synthesized present knowledge of the processes that contribute to the formation and evolution of near-surface salinity vertical salinity gradients and sub-footprint scale variability. The magnitudes of these gradients are quantified as a function of environmental conditions at scales relevant to satellite salinity, which is crucial for accurate formulation of the salinity error budgets and interpretation of present and future satellite salinity measurements.

Land-ocean processes

In May 2015, a record rainfall and flood event caused severe property damage and loss of human life in Texas. To create a comprehensive chronology of this event, **Fournier et al. (2016)** used a wide array of NASA satellite observations to analyze the extent of the 2015 Texas flood and its impacts on the coastal environment. The measurements included surface salinity and soil moisture from SMAP, precipitation from TRMM and GPM missions, water storage observations from GRACE, ocean color observations from MODIS instrument on board the Aqua satellite, and altimetric ocean currents from the Jason satellite series. By combining datasets from multiple satellite missions, the team presented a first, two-sided, ocean-to-land analysis, reporting high rainfall preceding the flood that caused soil saturation, record rainfall that generated record river discharge, and subsequently an unusual freshwater plume causing anomalous ocean currents in the coastal regions of the Gulf of Mexico. The latter may have significant biochemical implications.

Ocean hydrology impacting sea level estimate

The exchange of water between land and ocean through precipitation, evaporation, and winds has significant impacts on the global water mass balance. In a recent study, **Reager et al. (2016)** quantified this effect and its impact on calculation of the contribution of hydrologic mass variability on sea level budget estimates. Taking advantage of GRACE

measurements, the team estimated that as a result of climate changes, an additional 3200 Gt of water has been stored on land since 2002. This net groundwater storage partially offsets water losses from melting ice sheets, glaciers, and groundwater extraction, slowing down the rate of recent sea level rise by about 15%.

Ocean Physics/Ocean Solid Earth Interactions

Large-scale ocean processes such as tides and tsunami waves have a strong impact on coastal infrastructure. Understanding these processes and how the solid earth interacts with the ocean, e.g., during earthquakes, is of high importance to prepare for societal impacts.

Early tsunami warning established

For the Japanese tsunami on March 11, 2011, **Titov et al. (2016)** assessed two independent approaches that have been proposed to determine tsunami source energy: one inverted from the Deep-ocean Assessment and Reporting of Tsunamis (DART) data during the tsunami propagation, and the other derived from the land-based coastal GPS during tsunami generation. While the GPS approach takes into consideration the dynamic earthquake process, the DART inversion approach provides the actual tsunami energy estimation of the propagating tsunami waves; both approaches lead to consistent energy scales for previously studied tsunamis. They developed a real-time approach that combines the two methods: first, determine the tsunami source from the global GPS network immediately after an earthquake for near-field early warnings; and then, refine the tsunami energy estimate from nearby DART measurements for improving forecast accuracy and early cancelations. This methodology has been integrated into the NOAA early warning system.

Progress on understanding tides

With rising seas, the number of coastal flooding events can increase even at fairly normal high tides, with no additional contribution from storms, winds, or rain. These tidal flooding events are "nuisance" floods, which can affect large populations in low-lying coastal regions. Analysis of satellite altimeter data and tide-gauge records by **Ray and Foster (2016)** suggests that the nuisance flooding has markedly increased in recent years along the East Coast of the United States. Using different scenarios of future sea level rise, they predict further increase in the frequency and magnitude of tidal flooding events in the Boston area between now and 2050.

In addition to astronomical tides, new insights have been gained in understanding the effects of internal tides, which are waves in the ocean interior generated by surface tides. **Ray and Zaron (2016)** and **Zaron and Ray (2017)** use novel approaches to determine the signatures of internal waves using multi-mission altimeter data and inferences from ocean models. This new methodology is applied to the main semidiurnal (M_2) internal tide, and the resulting near-global maps were made available to the community. These maps are useful to interpret in situ ocean measurements with profiling

instruments, which generally sample the ocean interior with insufficient frequency to resolve tides, aliasing tidal variability to lower frequencies. The new maps by Zaron and Ray (2017) allow the effects of the internal tides to be removed from in situ data, improving the accuracy of measurements of the water mass vertical properties.

Earth System Model Improvements

Models supported by the CVC focus area include:

- The **NASA GISS Model E**, an Earth system model which is utilized for multidecadal studies of the climate system and understanding the various anthropogenic and natural factors influencing global change on decadal to multidecadal time scales.

- The **GEOS-5 Modeling System**, which includes the GEOS-5 modular Earth system model, the GEOS-5 data assimilation system, the GEOS-5 coupled chemistry/climate model, and the GEOS-5 chemistry and transport model.

- The **NASA Unified WRF** model, which is directed toward developing a comprehensive representation of the Earth system at regional scales.

A number of important improvements to the models and assimilation systems supported by the CVC focus area were made during the past year. The goal of these efforts was to produce more comprehensive, interactive and representative models, as well as more accurate analyses and reanalyses of the Earth system. Major highlights include:

- **Transition to operations of the GEOS 12.5-km hybrid 4D-EnVar atmospheric data assimilation system** on 24 January 2017 (replacing the 25-km 3D-hybrid system). This is a very important advance for the GEOS DAS, the culmination of years of development, which improves the skill of forecasts and the quality of the analyzed meteorological fields produced by the system. See, for instance: https://gmao.gsfc.nasa.gov/research/ science_snapshots/2017/Hyb-4DEnVar.php

- **Upgraded cloud processes in the GISS Model E:** All aspects of the moist physics in the GISS Model E3 GCM generation, which has been developed for participation in CMIP6, have been completely upgraded. The changes include (1) representation of cold pools and field experiment-based microphysics in the cumulus parameterization; (2) two-moment microphysics in the stratiform cloud parameterization, including prognostic variables for cloud water, cloud ice, rain, and snow mixing ratios and their number concentrations; (3) a moist turbulence approach for the convective boundary layer; and (4) a pdf-based approach for stratiform cloud fraction. These improvements allow the GISS Model E to successfully simulate the MJO, produce ice water paths consistent with CloudSat data, predict marine stratocumulus and shallow cumulus regimes in the geographic locations in which they are observed, reduce Southern Ocean shortwave biases, and simulate aerosol indirect effects based on microphysical processes.

Additional highlights include:

- **Development, implementation and validation of a new Eddy Diffusivity/Mass Flux (EDMF) boundary layer and shallow convection parameterization** into the GEOS-5 model, which is currently being evaluated for inclusion in the operational version of the model. The representation of the planetary boundary layer is critical to the proper representation of low-level stratocumulus cloud decks, which play an important role in the climate system and climate sensitivity.

- **A fully optimized adjoint of the Ice Sheet System Model:** Release of a fully optimized adjoint model of ISSM, enabling a new series of data assimilation experiments to integrate altimetry, velocity, GPS, and GRACE datasets into reconstructions of polar ice sheets and calibrations of model spin-ups.

- **A new radiative transfer model** ("Solar-J") for calculating photolysis rates and solar heating in climate models. It allows for rapid, consistent calculation in global models of both photolysis rates of important chemical species and the heating rates of the atmosphere and the Earth's surface. **(Hsu et al., 2017)**

- **Implementation of an ocean diurnal warm layer parameterization** in the GSFC GEOS Atmospheric Data Assimilation System (GEOS-ADAS), which has been shown to significantly improve the assimilation of hyperspectral satellite radiance measurements, improving the quality of the MAP-supported data assimilation system.

- **Coupling the STILT Lagrangian atmospheric transport model** to the NASA Unified Weather Research and Forecasting (NU-WRF) model in order to quantify source-receptor relationships needed to infer CO2 surface fluxes from atmospheric observations. This improves the capability to infer unmeasured quantities using models constrained by measurements, one of the goals of data assimilation.

- **Implementation of an updated GOddard SnoW Impurity Module (GOSWIM)** in the latest version of GEOS-5 to examine the impact of snow darkening on the interaction of rainfall, circulation and hydrology in monsoon regions. This improves the ability to understand feedbacks and interactions between different parts of the Earth system.

- **Model E ice particle parameterization: Elsaesser et al. (2017)** describe a new parameterization of ice particles for the GISS Model E which substantially improves the agreement of model predicted upper-tropospheric ice water content with observations.

Advances in Climate Modeling Science

Lau et al. (2016) examine how aerosols affect Indian monsoonal precipitation and circulation using the NASA Unified WRF model. They show that aerosol-radiation

interaction (ARI), *i.e.*, dust aerosol transport, and dynamical feedback processes induced by aerosol-radiative heating, plays a key role in altering the large-scale monsoon circulation system, reflected by an increased north-south tropospheric temperature gradient, and a northward shift of heavy monsoon rainfall, which advances the monsoon onset by 1–5 days over the Himalayan Foothills. The results indicate that even in short-term (up to weekly) numerical forecasting of monsoon circulation and rainfall, effects of aerosol-monsoon interaction can be substantial and cannot be ignored.

DelSole et al. (2017) investigate predictability on subseasonal time scales, which straddle the transition region between weather and climate. They find that an operational forecast model can skillfully predict week-3–4 averages of temperature and precipitation over the contiguous United States. The most predictable components of winter temperature and precipitation are related to ENSO, and other predictable components of winter precipitation are shown to be related to the Madden–Julian oscillation. These results establish a scientific basis for making week-3–4 weather and climate predictions.

Garfinkel et al. (2017) establish that changes in the Brewer-Dobson circulation over the past 25 years are influenced by multiple factors, including volcanic eruptions and changes in ozone-depleting substances. These factors can overwhelm the more general changes induced by greenhouse gas emission.

Huang et al. (2017) examine our skill at forecasting ENSO events – large coupled ocean/atmosphere climate fluctuations with global impacts. It shows that even with a sparser observing system, reforecasts have improved skill, indicating that improved modeling can improve forecasting. Improving ENSO forecasts could provide substantial economic benefits in addition to more complete understanding of the Earth system.

Advances in the modeling of the Madden-Julian Oscillation (MJO) were provided by **Jiang et al. (2016)**, which found the MJO amplitude to be closely tied to a model's convective moisture adjustment time scale. Also, **Ahn et al. (2017)** developed diagnostics specifically designed to isolate and evaluate the quality of the representation of the MJO in the suite of CMIP-5 models. Their approach is important when dealing with emergent processes in global models.

Lipat et al. (2017) provide clues to the understanding of the climate sensitivity of the models participating in the CMIP5 intercomparison, showing that models with equatorward Hadley cell circulations tend to have larger climate sensitivity values than models with more realistic placement of the Hadley cell.

Advances in Clouds and Cloud Process Modeling Science

Current global model parameterizations of cloud convection do not represent organized convection, a significant drawback. **Moncrieff et al. (2017)** describes a multiscale coherent structure parameterization that produces such organization and show that the parameterization produces simulations that are in better agreement with observations.

Such a parameterization may in the future be incorporated into a CVC-supported model to improve its representation of organized convection.

Camargo et al. (2016) evaluate the representation of tropical cyclones in GISS Model E and how their characteristics change as a result of increases in CO_2 and SST. Understanding how extreme weather might change in the future is a priority of the CVC focus area.

Global Earth system models typically neglect the radiative impact of precipitation. **Li et al. (2016)** show that there are important model biases resulting from this neglect, pointing the way toward improved model representations of the Earth's radiative characteristics. **Cesana and Waliser (2016)** evaluate the 3-D representation of clouds in a suite of global models using NASA CALIPSO satellite data, and find that these models tend to overestimate high clouds over oceans and in moist environments, while underestimating them compared to observations over land and in dry environments.

Advances in Modeling of Oceans and Atmosphere/Ocean Coupling

Marshall et al. (2017) explore the influence of the representation of small-scale ocean circulation processes (mesoscale eddies) on larger-scale transport representation (the meridional overturning circulation). Interestingly, the Atlantic meridional overturning circulation is sensitive to Southern Ocean eddy processes, demonstrating the need for a global perspective. This suggests that higher resolution modeling which represents eddy structures well is important for successful modeling of ocean transport processes.

Modeling of ocean biological systems depends critically on the representation of radiative transfer in the ocean. **Gregg and Rousseaux (2016)** examine the sensitivity of ocean biology to radiative transfer, and shows that including directional and spectral irradiance is important.

Gregory et al. (2016) describe a model intercomparison project to investigate the response of coupled ocean/atmosphere model sea level and ocean circulation to imposed perturbations of heat, momentum, and freshwater to the ocean surface. This furthers the CVC goal of understanding and modeling the coupled ocean/atmosphere system and uncertainty in model predictions of response to perturbations.

Advances in Modeling of Land/Atmosphere Coupling

Broxton et al. (2016) identify the misrepresentation of snow ablation processes in global models as a cause of the common underestimate of snow water equivalent in global reanalyses. Snow water equivalent is an important quantity to represent well due to its importance in understanding and predicting drought, an important goal of the CVC focus area.

Estimates of snow water equivalent depend on snow density. **Dawson et al. (2017)** present a new physically based snow density parameterization which has the potential to improve estimates of snow water equivalent in operational models.

Lawston et al. (2017) discuss the representation of irrigation in the NOAH land surface model and use NASA's Land Information System (LIS) to evaluate the scheme in comparison with observations. It is consistent with the CVC focus area's emphasis on representing the Earth system comprehensively and rigorous evaluation of model results with observations.

Cryospheric Modeling

Larour and Schlegel (2016) describe the porting of the CVC-supported Ice Sheet System Model (ISSM) to the Amazon EC2 cloud, and the first-ever application of cloud computing to the modeling of polar ice flow. The advantage of cloud computing is the potential to remove long wait times on high-end clusters. They argue that a mix of high-end parallel computing and cloud computing can accelerate the delivery of climate projections and uncertainty quantification that has been to date difficult to achieve. NASA modeling is often computational resource limited, and the results of this paper indicate that new computing paradigms may provide substantial benefits to NASA.

Ice flow is a critical process in the context of ice sheet simulation and predictions of sea-level rise. Properly representing ice sheets in global models is a priority of the CVC focus area. **Habbal et al. (2017)** describe the testing of a large number of available numerical solvers in the context of simulating ice flow, and provides recommendations for solvers that will enable higher resolution simulation of ice sheets.

Modeling polar ice sheet evolution constrained by observations requires computation of adjoints. **Larour et al. (2016)** describe modifications/techniques, such as operator overloading, that facilitate adjoint computation of the CVC-supported ISSM. Their techniques will allow projections which are improved due to the ability to successfully evaluate the forward model using observations and the adjoint technique.

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FY 2017 Annual Performance Indicator	FY 14	FY15	FY16	FY17
ES-17-9: 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-17-11:</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, https://science.nasa.gov/earth-science/focus-areas/surface-and-interior) continues to advance the understanding of core, mantle, and lithospheric structure and dynamics, and interactions between these processes and Earth's fluid envelopes. Research conducted in the past year has also provided the basic understanding and data products needed to inform the assessment and mitigation of natural hazards, including earthquakes, tsunamis, landslides, and volcanic eruptions. ESI's Space Geodesy Program (SGP) continues to produce observations that refine our knowledge of Earth's shape, rotation, orientation, and gravity, foundational to many Earth missions and location-based observations.

The ESI strategy is founded on the seven scientific challenges identified in the *Challenges and Opportunities for Research in ESI (CORE) Report*, published in December 2016 (Davis et al, 2016, http://go.nasa.gov/2hmZLQO):

1. What is the nature of deformation associated with plate boundaries and what are the implications for earthquakes, tsunamis, and other related natural hazards? [Plate boundaries]
2. How do tectonic processes and climate variability interact to shape Earth's surface and create natural hazards? [Tectonics and surface processes]
3. How does the solid Earth respond to climate-driven exchange of water among Earth systems and what are the implications for sea-level change? [Solid Earth and sea level]
4. How do magmatic systems evolve, under what conditions do volcanoes erupt, and how do eruptions and volcano hazards develop? [Magmatic systems]
5. What are the dynamics of Earth's deep interior and how does Earth's surface respond? [Deep Earth]
6. What are the dynamics of Earth's magnetic field and its interactions with the rest of the Earth system? [Magnetic field]
7. How do human activities impact and interact with Earth's surface and interior? [Human impact]

Highlights of research and accomplishments of the past year, and their connections to addressing the *CORE* challenges, are summarized below.

<u>Lithospheric Processes</u>

Lithospheric structure and dynamics, and interactions between these processes and the oceans, hydrologic system, and atmosphere are critical to understanding the Earth system. This includes the motion and rotation of tectonic plates, elastic properties of the crust, and the effects of surface loading resulting from surface water, ground water, other fluids,

glaciers, and ice sheets. These studies also represent enabling research for the hazards advancements described in a subsequent section.

There were two cornerstone manuscripts that focused on the fundamentals of GPS and GPS network processing, collectively providing a perspective on how GPS has evolved into an essential component of ESI's portfolio. Bock and Melgar (2016) is a 119-page review manuscript on the current state-of-the-art for GPS geodesy that is effectively a textbook for GPS tectonic geodesy. In brief, their paper reviews the relevant concepts of geodetic theory, data analysis, and physical modeling for a myriad of processes at multiple spatial and temporal scales, and discusses the extensive global infrastructure that has been built to support GPS geodesy, consisting of thousands of continuously operating stations. They discuss the integration of heterogeneous and complementary data sets from geodesy, seismology, and geology, focusing on crustal deformation applications and early warning systems for natural hazards. GPS and the expanding multi-GNSS constellations are essential to advancing our understanding of solid-Earth, lithospheric, and natural hazard processes. Herring et al. (2016) is a review manuscript on how GPS data is processed by the Geodesy Advancing Geosciences and EarthScope (GAGE) Facility GPS Data Analysis Centers. The primary products that they generate are the position time series that show motions relative to a North America reference frame and secular motions of the stations represented in the velocity field. The position time series themselves contain a multitude of signals in addition to the secular motions. Coseismic and postseismic signals, seasonal signals from hydrology, and transient events, some understood and others not yet fully explained, are all evident in the time series and ready for further analysis and interpretation. They also explore the impact of analysis assumptions on the reference frame realization and on the final solutions. Collectively, the approaches described by these manuscripts either directly enable or support the science that span nearly every *CORE* challenge: 1. [Plate boundaries], 2. [Tectonics and surface processes] 3. [Solid Earth and sea level], 4. [Magmatic systems], 5. [Deep Earth], and 7. [Human impact].

The scientific analysis of GPS network data with hundreds to thousands of GPS/GNSS sites, as showcased in the Bock and Herring manuscripts, is spawning the development of new and innovative approaches to isolate solid-Earth geodetic signals within the GPS time series. Hammond et al. (2016) describe a new method they call 'GPS Imaging,' for selecting, filtering, and interpolating *vertical* velocities to generate robust maps of the vertical velocity field associated with flex and flow of the solid Earth. Their approach can best be described as a hybrid between image-processing-style median spatial filtering and geostatistical kriging, and it enables the recognition of the vertical motion associated with elastic strain accumulation on faults, magmatic deformation, viscous postseismic relaxation, tectonic uplift, subsidence from groundwater extraction, and related elastic rebound. They apply the approach to the Sierra Nevada Mountain range and find that the Sierra Nevada is the most rapid and extensive uplift feature in the western United States, rising up to 2 mm/yr along most of the range. The uplift is juxtaposed against domains of subsidence attributable to groundwater withdrawal in California's Central Valley. The uplift boundary is consistently stationary, although uplift is faster over the 2011–2016 period of drought. Uplift patterns are consistent with groundwater extraction and

concomitant elastic bedrock uplift, plus slower background tectonic uplift. A discontinuity in the velocity field across the southeastern edge of the Sierra Nevada reveals a contrast in lithospheric strength, suggesting a relationship between late Cenozoic uplift of the southern Sierra Nevada and evolution of the southern Walker Lane. The approach developed by Hammond et al. will have wide application across the *CORE* challenges: 1. [Plate boundaries], 2. [Tectonics and surface processes], 3. [Solid Earth and sea level], 4. [Magmatic systems], 5. [Deep Earth], and 7. [Human impact].

ESI-funded researchers use a variety of geodetic and seismic techniques to model pre-, co-, and post-seismic measurements to better understand the structure and rheology of the lithosphere. Huang et al. (2016) integrated GPS, InSAR and seismic measurements for the 2016 M_w 6.4 MeiNong earthquake in southwest Taiwan and found that while the primary earthquake ruptured between 15–20 km depth, their geodetic data resolved triggered slip on a shallower thrust at 5–10 km depth. This shallower thrust coincides with a proposed duplex located in a region of high fluid pressure and high interseismic uplift rate. Their results imply that under tectonic conditions such as high-background stress level and high fluid pressure, a moderate lower crustal earthquake can trigger faults at multiple levels in upper crust. Large earthquakes often trigger viscoelastic adjustment for years to decades depending on the rheological properties and the nature and spatial extent of coseismic stress. Han et al. (2016) analyzed GRACE data for the paired 2006 Mw8.3 thrust and 2007 Mw8.1 normal fault earthquakes in the central Kuril Islands and found significant postseismic gravity change that both lack discernible coseismic gravity change. The gravity increase of ~4 μGal, observed consistently from various GRACE solutions around the epicentral area during 2007–2015, is interpreted as resulting from gradual seafloor uplift by ~6 cm produced by postseismic relaxation. The GRACE data are best fit with a model of 25–35 km for the elastic thickness and ~10^{18} Pa s for the Maxwell viscosity of the asthenosphere. The large measurable postseismic gravity change (greater than coseismic change) emphasizes the importance of viscoelastic relaxation in understanding tectonic deformation and fault-locking scenarios in the Kuril subduction zone. These are two of a number of publications that addressed *CORE* challenges: 1. [Plate boundaries] and 5. [Deep Earth].

Deep-Earth Processes

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

Highlighting the interdisciplinary significance of the mantle in Earth-system processes, Richter et al. (2016) analyzed GNSS observations at 43 sites across the Southern

Patagonian Icefield region to reveal the magnitudes and patterns of vertical and horizontal present-day crustal deformation, as well as their primary driving processes. They observed rapid uplift of up to 41 mm/yr related to glacial-isostatic adjustment (GIA) that points to preferred mantle model including lateral viscosity heterogeneity and an effective upper mantle viscosity <1.6×10^{18} Pa·s. The observed deformation field suggests significant contributions from GIA, a western interseismic tectonic deformation field related to plate subduction, and an extensional strain-rate field related to active Patagonian slab window tectonics, advancing understanding of questions that cross *CORE* 1. [Plate boundaries], 2. [Tectonics and surface processes] 3. [Solid Earth and sea level], and 5. [Deep Earth].

Directly aligned with the *CORE* 5. [Deep Earth] goal of exploring the coupling between deep-Earth and surface processes, Sembroni et al. (2017) performed experiments to investigate the role of the lithosphere on dynamic topography, which is a surface expression of mantle-flow induced stresses associated with deep density anomalies. They studied the topographic signal of a rising mantle anomaly and found that a layered lithosphere may modulate the signal, with the uplift rate and the geometry of the surface bulge being inversely correlated to lithosphere thickness.

Several geomagnetic contributions addressed *CORE* 5. [Deep Earth] and 6. [Magnetic field], from improving understanding of the upper-mantle, to advancing tools and models for studying field dynamics and electromagnetic sounding of properties from the core to the near-surface. Ocean tidal flow drives an electrically conductive fluid through the geomagnetic field, resulting in the generation of secondary magnetic signals, which can provide information on subsurface structure. Grayver et al. (2016) demonstrated that tidal magnetic signals detected by satellites can be used to retrieve information on the electrical structure of the upper mantle. They imaged the global electrical structure of the oceanic lithosphere and upper mantle down to a depth of ~250 km. Their model, derived from more than 12 years of satellite data, reveals a ~72-km-thick upper resistive layer followed by a sharp increase in electrical conductivity likely associated with the lithosphere-asthenosphere boundary, which separates colder, rigid oceanic plates from the hotter, ductile asthenosphere.

The Earth's magnetic field is generated by convection in the liquid iron alloy outer core. Understanding the origin and evolution of the Earth's magnetic field and the dynamics of the outer core are grand challenges in geophysics and fundamental to *CORE* 5. [Deep Earth] and 6. [Magnetic field]. Numerical dynamo simulations have played a central role in these studies, though they have been hampered by resolution limitations that result in thermal diffusivities that are much larger than those in the Earth's core. Matsui et al. (2016) performed a benchmarking study of numerical dynamo simulators, including the Goddard Space Flight Center Modular, Scalable, Self-consistent, and Three-dimensional (MoSST) model, to assess the performance of different numerical methods in test cases on up to 16,000+ processor cores. They found that dynamo codes employing 2D or 3D domain decompositions can perform efficiently on up to ~10^6 cores, paving the way for higher-resolution and more realistic simulations in next generation models.

The POMME-11 Geomagnetic Field Model was also released this year (Maus, 2016, http://geomag.org/models/pomme11.html). The spherical harmonic degree 133 model uses data from the CHAMP, Oersted, and Swarm satellites spanning 2000 to 2016. POMME is a scientific main field model representing the geomagnetic field in the region from the Earth's surface to an altitude of a couple of thousand kilometers. Models of the main and external field play a key role in the analysis and interpretation of satellite, airborne, marine and ground magnetic data, and POMME-11 is one reference for these studies.

Natural Hazards Research

New and innovative natural hazards research and analysis is providing insights into earthquake, landslide, and volcanic processes, along with new geodetic analysis approaches for advancing scientific understanding and hazard early warning capabilities. Human activity is increasingly being measured in geodetic time series, most notably associated with the pumping of fluids (groundwater and hydrocarbons). There have been a number of high-profile earthquakes attributed to fracking/hydrocarbon production that have renewed interest in advancing our understanding and characterization of how human activity impacts regional and local hazards, including induced seismicity. In 2017 there was a newly competed Interdisciplinary Research in Earth Science (IDS) ROSES solicitation that added 5 new projects studying the physics that drive cascading hazards, specifically, the relationship between solid-Earth and fluvial hazards.

Four of the seven *CORE* challenges are specific to Natural Hazards research: 1. [Plate boundaries], 2. [Tectonics and surface processes], 4. [Magmatic systems], and 7. [Human impact]. Furthermore, Natural Hazards are represented in the *CORE* report in Section 3.2 as a Science Enabler and a driver for many 'low-latency data and data products;' Section 3.4, The Increasingly Interconnected World, where hazards transcend geopolitical boundaries and can cross oceans, thereby requiring international cooperation; Section 3.5, where understanding natural hazards has direct Societal Benefits; and Section 3.7, International and Interagency Cooperation, where the sharing of geodetic data, imagery, analysis, and algorithms help develop robust situational awareness capabilities during major disasters, thereby supporting our sister agencies and international relief efforts. Below is a brief synopsis of a few ESI-supported publications that contributed to our understanding of Natural Hazards during this past year.

The *Science* article by Hamling et al. (2017) had a research team of 29 co-authors from 11 national and international institutes that combined satellite radar interferometry and GPS data to understand the intricacies of the M 7.8 Kaikoura earthquake in New Zealand. The team found that the Nov. 14, 2016, earthquake was likely the most complex earthquake in modern history, during which parts of New Zealand's South Island moved more than 5 meters closer to New Zealand's North Island and were uplifted by as much as 8 meters. The quake ruptured at least 12 major crustal faults along with evidence of slip along the southern end of the Hikurangi subduction zone plate boundary, which lies about 20 kilometers below the North Canterbury and Marlborough coastlines. Understanding how all these faults moved in one event will improve seismic hazard models. This

manuscript contributed to *CORE* 1. [Plate boundaries] and 2. [Tectonics and surface processes].

The 3 September 2016 Mw 5.8 Pawnee earthquake shook a large area of north-central Oklahoma and was the largest instrumentally recorded earthquake in the state. Fielding et al. (2017) developed a time-series SAR intergerogram stack from the Sentinel-1A and Sentinel-1B and RADARSAT-2 satellites and fit a step function at the time of the Pawnee earthquake that resolved about 3 cm peak-to-peak amplitude of the coseismic surface deformation in the radar line of sight with a spatial pattern that is consistent with fault slip on a plane trending east-southeast. They named the previously unrecognized lineament the Sooner Lake fault (SLF). Their preferred slip model on the SLF has no slip shallower than 2.3 km depth, an area of moderate slip extending 7 km along strike between 2.3 and 4.5 km, and larger slip between 4.5 and 14 km depth extending about 12 km along strike. The 10–11-km centroid depth of the finite-fault slip for the Mw 5.8 Pawnee earthquake that they derive from the InSAR data is more than twice as deep as their relocated hypocenter initiation depth of 4.5 km; therefore, they conclude that the rupture must have propagated down-dip into the basement rocks. This is consistent with the USGS NEIC W-phase moment tensor centroid depth of 11.5 km and is consistent with the earthquake initiation at a shallower location affected by fluid injection. This research contributes to *CORE* 7. [Human Impact].

The Central Apennines in Italy have had multiple moderate-size but damaging shallow earthquakes. Huang et al. (2017) analyzed the fault geometry and invert for fault slip based on coseismic GPS and interferometric synthetic aperture radar (InSAR) for the 2016 Mw 6.2 Amatrice earthquake in Italy. Their results showed that nearly all the fault slip occurred between 3 and 6 km depth but extends 20 km along strike. There was less than 4 cm static surface displacement at the town of Amatrice, where the most devastating damage occurred. The along fault slip distribution from their model indicates two distinct slip asperities, which is in agreement with a published seismic inversion investigation. Landslides triggered by earthquake ground shaking are not uncommon, but triggered landslides with submeter movement are challenging to observe in the field. This investigation identified coseismically triggered deep-seated landslides northwest and northeast of the epicenter where coseismic peak ground acceleration was estimated >0.5g and they were able to estimate the landslide thickness as at least 100m and 80m near Monte Vettore and west of Castelluccio, respectively, by combining ascending and descending InSAR data. They also found that the landslide near Monte Vettore terminated on the preexisting Monte Vettore Fault scarp and they cautioned that paleoseismic studies that assess the long-term fault slip rate in this region could potentially have errors due to these deep-seated earthquake triggered landslides. This manuscript contributed to *CORE* 1. [Plate boundaries] and 2. [Tectonics and surface processes] and to our understanding of cascading hazards.

This past year saw significant advances in mesospheric/ionospheric research for earthquake and tsunami detection, characterization, and real-time early warning capabilities (*CORE* 1. [Plate boundaries]). Atmospheric gravity waves (AGW) triggered by earthquakes and tsunamis travel up the atmospheric column through mesosphere and

ionosphere, where the effect of the AGW can be detected and measured by airglow in the mesosphere and with GNSS measured total electron content (TEC) in the ionosphere. Yang et al. (2017) retrieved tsunami-induced airglow emission perturbations with space-based measurements made by the Sounding of the Atmosphere using Broad-band Emission Radiometry (SABER) instrument onboard the Thermosphere-Ionosphere-Mesosphere Energetics Dynamics (TIMED) spacecraft for both the Tohoku-Oki earthquake on 11 March 2011, and the Chile earthquake on 16 September 2015. Airglow observations and model simulations suggest that atmospheric neutral density and temperature perturbations can lead to the observed amplitude variations and multi-peak structures in the emission profiles. This was the first time that airglow emission rate perturbations associated with tsunamis have been detected with space-based measurements. Zettergen et al. (2017) further analyzed and modeled the influence of the Tohoku-Oki earthquake on the ionosphere. They found that large AGW can produce a pronounced TEC depletion within the ionosphere; these "holes" are above the source region and have been observed on multiple occasions. They believe it may be possible to estimate the amplitude of a tsunami based on its ionospheric signature. Finally, Savastano et al. (2017) developed a real-time GNSS algorithm for the detection of traveling ionospheric disturbances (TIDs) associated with earthquakes, tsunamis, volcanic eruptions and man-induced explosions. They successfully tested the algorithm named VARION (Variometric Approach for Real-Time Ionosphere Observation) with the 2012 Haida Gwaii, Canada tsunami event that was measured in Hawaii. This innovative approach may be able to detect a tsunami upwards of 150 km before it makes landfall, and thereby provide over an hour of early warning that a tsunami is approaching.

ESI participated in coordination, support, and implementation of the HyspIRI Hawaii Preparatory Airborne Campaign, including five ROSES research projects studying volcanic emissions and eruptive activity. In January-March 2017, scientists from NASA, the USGS Hawaiian Volcano Observatory (HVO), Hawaii Volcanoes National Park, and several universities embarked on a six-week field campaign to study the links between volcanic gases/thermal emissions and vegetation health and extent, the flow of lava from the volcanoes, thermal anomalies, gas plumes, and ways to mitigate volcanic hazards. While scientists collected in-situ calibration and validation data across the active volcano, NASA's ER-2 aircraft carried the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) and the MODIS-ASTER Airborne Simulator (MASTER) overhead. The campaign, which also studied Hawaii's coral reefs, provided precursor data for NASA's Hyperspectral Infrared Imager (HyspIRI) satellite mission concept to study Earth ecosystems and natural hazards such as volcanoes, wildfires and drought. Data from the airborne campaign are available at https://hyspiri.jpl.nasa.gov/airborne.

Geodetic Imaging

Synthetic aperture radar (SAR) and interferometric SAR (InSAR) data are critical to enabling most of the *CORE* objectives with a focus on surface deformation. Significant contributions continued to flow from UAVSAR, and progress continued towards realizing the NASA-ISRO Synthetic Aperture Radar (NISAR) satellite mission.

NISAR successfully conducted its KDP-C gate review in August 2016, thereby entering Phase C. With the project in implementation, the science element – including the project science team and the NASA-appointed NISAR Science Team (ST) – turned to adding greater fidelity and specificity to its deliverables. The addition of an applications point-of-contact on the ST just prior to KDP-C led to reevaluation of the observation plan. Many applications require finer resolution than were scheduled in the preliminary design. The applications lead worked with the ST as a whole to add finer resolution over the U.S. Many of these applications, including critical infrastructure monitoring, use similar time-series data sets and analysis techniques as are used in the solid-Earth sciences. ISRO scientists also refined their observation plan, adding additional targets and higher data-rate modes. These changes have put pressure on the data system, and the science team has worked with mission planners to evaluate alternate observation scenarios that accommodate the changes and still meet requirements. The science element supported the NISAR Science Workshop held in Ahmedabad, India, in November 2016, and two Science focused technical meetings (FTMs) in Ahmedabad in January and July 2017. At the FTMs, NASA and ISRO scientists discussed scientific and geographic areas of common interest and wrote white papers describing a joint science plan to be developed. There were also NISAR science team meetings held at JPL in September 2016, February 2017, and May 2017. The NISAR project scientist gave presentations on NISAR at the Fall AGU meeting in San Francisco, several venues in India, and at IGARSS 2017 in Ft. Worth.

The applications subgroup held focused workshops on critical infrastructure and sea-ice applications in June 2017. They also developed a NISAR Utilization Plan for NASA's Applied Sciences Program, and an Urgent Response Framework for engaging NASA and other agencies in setting priorities and response activities in the event of disasters, many of which may be related to the solid Earth, such as earthquakes, volcanoes, and landslides.

One of the key science trades for the Solid Earth subgroup has been the overall left-looking/right-looking strategy for observing both poles. SAR systems must point their antenna beam in a direction squinted away from the velocity vector, ideally perpendicular to the flight track. Generally, the ESI community optimizes their science by looking to only one side of the spacecraft, giving continuous time series. However, to observe both poles, the nominal plan looks to the north for 25 cycles out of the year and to the south 5 cycles per year. The Solid Earth team has advocated for partnerships with other agencies to cover the north polar cap so that NISAR can look continuously to the south. The mission team has evaluated various scenarios at the request of the science team, and further studies are ongoing.

An innovation introduced by the Solid Earth subgroup is the geocoded complex image product, one that has never been produced operationally before but that could greatly simplify the use of these data by non-expert scientists. The ST also refined the algorithms for correcting interferometric deformation data for ionospheric effects, demonstrating methods that work not only with two time steps but a time-series of data similar to what will be available for NISAR. In an example of how algorithm development is advancing

ahead of mission launch, Fattahi et al. (2017) described a version of the network-based workflow that NISAR will employ, using terrain observation by progressive scan (TOPS) time-series as a surrogate data set.

Between July 16, 2016 and July 15, 2017, UAVSAR's L-band radar conducted 57 science/engineering flights and acquired 563 flight lines totaling 9.3 TB of raw data over the U.S. The P-band AirMOSS radar conducted 14 science/engineering flights and acquired 100 flight lines over California, Alaska, and Canada, while the Ka-band GLISTIN-A radar conducted 37 science/engineering flights and acquired 305 flight lines over the Continental U.S. and Greenland. These observations catalyze innovative studies that will pave the way for global monitoring initiatives with spaceborne instruments.

In the fall of 2016, UAVSAR imaged Hawaii's Big Island at regular intervals over the course of 24 hours. Owing to its dynamic weather and topographic gradient, this study site is ideal for measuring the impact of air moisture on radar retrievals. Results will enable researchers to improve techniques to estimate ground movement. In February 2017 GLISTIN-A also flew to the Big Island to acquire topography data to demonstrate the capacity for the technique to constrain lava effusion rates. Topography is one of the most fundamental datasets for any volcano and GLISTIN-A's single-pass InSAR capability could provide that. Repeat GLISTIN-A acquisitions would provide topography change. Combined with InSAR, these observations have the potential to greatly improve our physical understanding of volcanoes.

In support of ESI research, UAVSAR has continued to overfly western U.S. faults and landslides. This includes a joint NASA-USGS project to use UAVSAR, space-based InSAR, and mobile laser scanning (MLS) to study Northern and Central California faults that exhibit different degrees of shallow fault slip and/or rupture. The study seeks to see if the improved precision resulting from the coupled measurements can provide better understanding and predictive power of potential earthquake rupture and/or afterslip. Another study of California faults focuses on the use of UAVSAR to understand "flower" structures, which arise when a fault bends, creating several faults at the surface that coalesce into a single fault at depth. Flights over landslides in California and Colorado are providing critical information that can be used to improve and develop predictive landslide models, and also help in designing future InSAR systems to better image landslide motion.

Meanwhile, scientists continue to make use of UAVSAR imagery from past airborne campaigns. Overall science results based on UAVSAR data were published in 25 refereed journal papers, some of which are highlighted above, covering topics in applied science, cryosphere, hydrology, land cover/land use change, solid earth, space archaeology, and terrestrial ecology. Publications are continuously updated on the UAVSAR website at http://uavsar.jpl.nasa.gov/cgi-bin/publications.pl.

Space Geodesy Program

NASA's Space Geodesy Program (SGP) (http://space-geodesy.nasa.gov/) supports the production of foundational geodetic data that enable many of the scientific discoveries and accomplishments highlighted in the other sections, providing important underpinning for all of the *CORE* challenges. During the past year, SGP continued the development and deployment of a modern network that includes co-located next-generation Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite System (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) stations.

The SGP completed the commissioning of the joint NASA-United States Naval Observatory broadband VLBI Global Observing System (VGOS) station at NASA's Kōke'e Park Geophysical Observatory (KPGO) in Hawaii. The station is now operational. In May 2017, a 24-hour VGOS test session was successfully performed using the new KPGO station along with the broadband stations at Westford in Massachusetts, Goddard Geophysical and Astronomical Observatory (GGAO) in Maryland, Wettzell in Germany, and Yebes in Spain. This session is a first of its kind with the KPGO-Wettzell baseline being the first trans-Pacific/Arctic/Atlantic VGOS measurements ever.

SGP also continued to develop a new multi-technique geodetic site at the McDonald Observatory in Texas. The development effort for the new Texas SLR station passed several critical review milestones, including a Critical Design Review for the Gimbal and Telescope Assembly. Development of the Texas VGOS signal chain began based on the KPGO design, and a contract was awarded to Intertronic Solutions Inc. to build the Texas VGOS antenna.

Modernization of NASA's Global GNSS Network is underway with new deployment of state-of-the-art, multi-GNSS receivers capable of generating measurements from all major Global Navigation Satellite Systems (GNSS). This effort also ensures the Network will be capable of supporting the upcoming GPS Block III satellites, co-located space geodetic measurement techniques, and will continue to support precise timing applications. To take advantage of access to multi-GNSS measurements, the Jet Propulsion Laboratory (JPL) successfully delivered new, modernized analysis software *GipsyX* into operations, producing GPS precise orbit solutions. These solutions are the critical input used by NASA's Earth Science missions and scientists for precise positioning and timing using GPS. Research was initiated into how the new software's multi-GNSS analysis capabilities and access to multi-GNSS data can be leveraged to better support Geodesy and its science applications.

NASA made significant progress in engaging international and other agency partners, critical to realizing the goals of the Global Geodetic Observing System. The SGP completed negotiations with the Norwegian Mapping Authority on an agreement for the development and implementation of a NASA SLR station in Ny-Ålesund, Norway, a unique location within the Arctic Circle that will be particularly valuable in supporting the tracking of NASA's polar orbiting satellites. The agreement was signed during a visit of the Norwegian delegation to NASA Headquarters on August 7, 2017. The SGP also

evaluated a potential site in Tahiti for a new joint NASA-CNES geodetic site, and started the development of a joint implementation plan for that site.

NASA, the Department of Navy, and the National Oceanic and Atmospheric Administration (NOAA) renewed their agreement for the National Earth Orientation Service, continuing their long and very productive partnership in Space Geodesy.

The SGP plays an important role in the United Nations initiative to marshal international support for a globally-coordinated approach to geodesy. This initiative, coordinated by the UN Committee of Experts on Global Geodetic Information Management (UN-GGIM), provides support for a global effort that no one country is capable of doing alone, and stresses the significance of reference frames in supporting sustainable development. Four members of SGP participated in the Seventh Session of the UN-GGIM July 31 – August 4, 2017, at UN Headquarters in New York, with a focus on engaging in and supporting the formal institution of a Subcommittee on Geodesy.

It was another record year for NASA Space Geodesy Network operations, and utilization of attendant data products. The NASA Satellite Laser Ranging (SLR) network 2016 annual total data yield was equivalent to the prior best record year in 2015. NASA's VLBI stations also continue to be among the most productive of the global VLBI network, which had the third-highest number of station days observed in 2016 – a 50% increase over a decade ago. NASA's global space geodesy data archive and distribution system, the Crustal Dynamics Data Information System (CDDIS), broke previous data distribution records by 30%, with 1.5 billion downloads and 170 terabytes of data transferred in 2016.

Preparations for the next International Terrestrial Reference Frame (ITRF) have begun. The ITRF is a reference frame common to all position and timing applications within NASA and the commercial world. Building on JPL's experience in developing NASA's first ITRF solution in 2015 and utilizing JPL's expertise in GPS data analysis, development of new software for combining products from all four space geodesy techniques was initiated. In addition, development was initiated that will allow TRF solutions by combining observations. This latter approach has the potential to significantly improve the ITRF using existing observations. Software development and validation is expected to be complete in 2019, setting the stage for full participation in the next ITRF, expected in 2020.

Strategic Development and Community Engagement

The ESI Focus Area works with agency partners, the solid-Earth research community, and other stakeholders to identify and advance key science objectives and promote awareness of the program.

The *CORE Report* (Davis et al, 2016) was published in December and distributed electronically and in hard copy at the 2016 Fall AGU Meeting. The report serves as the latest comprehensive input to ESI's vision.

Another report, *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing (ERUPT)* (NASEM, 2017), delves into the challenges raised in *CORE* 4. [Magmatic systems]. The product of a study co-sponsored by ESI, NSF, and USGS, the *ERUPT Report* highlighted the need for satellite measurements of ground deformation and gas emissions, drone observations, advanced seismic monitoring, and real-time high-speed acquisition of data during eruptions. Of particular relevance to NASA were findings on perceived value of higher spatial and temporal (towards daily) resolution of volcano observations to facilitate greater understanding of volcanic processes and improve eruption forecasting and warnings.

ESI supported two disciplinary workshops with topics that span the Earth system from the core to the ionosphere. *Understanding the Earth's Core and Nutation,* held in September 2016 in Brussels, Belgium, explored observations, theory, and modeling of the physical processes inside the Earth associated with Earth rotation and nutation, with a focus on core-mantle boundary processes and connections to the geodynamo (*CORE* 5. [Deep Earth] and 6. [Magnetic field]). The workshop was co-convened by Veronique Dehant of the Royal Observatory of Belgium and Richard Gross of the Jet Propulsion Laboratory (JPL) and highlighted in EOS (Dehant, 2017). The *GNSS Tsunami Early Warning System Workshop* held in July 2017 in Sendai, Japan, was a collaboration between NASA and the Association of Pacific Rim Universities (APRU) to take next steps towards a future Global Navigation Satellite System Tsunami Early Warning System (GNSS-TEWS) (*CORE* 1. [Plate boundaries]). Workshop participants identified what GNSS resources (networks, processing centers, telecommunication, etc.) will be necessary to develop real-time GNSS early warning capabilities throughout the entire Pacific Rim region, assessed data gaps in the current Pacific-wide networks, developed strategies on the best approaches to fill the gaps, and reviewed state-of-the-art early warning approaches, with an eye towards the emergency response community. Opportunities for GNSS tsunamigenic earthquake source constraints, as well as the tracking of tsunami-induced ionospheric plasma disturbances through GNSS measurement of the total electron content (TEC), were explored.

ESI coordinated with the National Academy of Sciences, Engineering, and Medicine (NSAEM) and JPL to host the May 2017 Spring Meeting of the Board on Earth Sciences and Resources, *Space Observations of Earth's Surface, Interior, and Dynamics*, on the JPL campus. The agenda sought to give the board a better appreciation for how Earth science is conducted at NASA, exploring the mission lifecycle and chronicling several success stories, including a presentation on GRACE by JPL Director Mike Watkins and further discussions of NISAR and UAVSAR, and geodetic infrastructure. Other participants included JPL Director for Earth Science and Technology Diane Evans, JPL Chief Scientist Mark Simons, and Scott Pace, who is the newly selected Executive Secretary of the National Space Council. Key takeaways by the Board were a greater appreciation for the timescales involved in mission development, and how ESI's opportunity space is constrained within the broader landscape of Earth science mission priorities. They expressed interest in working with ESI on next steps for advancing solid-Earth priorities after the upcoming release of the Decadal Survey for Earth Science and

Applications from Space. This was the first time a full NASEM Earth sciences board had met on the JPL campus. Board staff are working on a "Meeting in Brief" summary to distribute to key stakeholders.

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FY 2017 Annual Performance Indicator	FY 14	FY15	FY16	FY17
ES-17-11: 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

APPENDIX

In late 2017, initial results from the OCO-2 satellite, launched in 2014, five papers were published in a special collections issue of Science Magazine. Topics of the special collection discussed the detection of specific point–source CO_2 emissions (Schwander et al., 2017); measurements of CO_2 variations associated with El Niño (Eldering et al., 2017); El Niño effects on land (Liu et al., 2017) and the Tropical Pacific Ocean (Chatterjee et al., 2017); and observations of solar-induced fluorescence (SIF) by chlorophyll to estimate gross primary production (photosynthesis) by plants (Sun et al., 2017). This brief appendix describes the interdisciplinary Earth system results and analyses from the OCO-2 satellite.

Eldering et al., (2017) provided an overview of the rationale, overview and conclusions from early results from NASA's OCO-2 satellite. The oxygen A-band (centered at ~765 nm) provides a sensitive measure of the atmospheric path length and is thus an accurate indicator of clouds and surface elevation. The radiance at two distinct CO_2 absorption bands (1.61 and 2.06 mm) provides sensitivity to CO_2. The column-averaged atmospheric CO_2 dry air mole fraction (XCO2), or the total column of carbon dioxide normalized by the column of dry air, is derived from these spectra using a physics based retrieval method. The sensitivity of the measurement is fairly uniform throughout the troposphere and lower stratosphere and varies with solar geometry and surface.

The massive 2015–2016 El Niño contributed to the anomalously large XCO_2 growth rate. The OCO-2 mission started approximately 6 months before the beginning of the El Niño. The 3 ppm global increase in XCO_2 recorded during this El Niño is one of the largest ever observed, consistent with previous research that has shown that global CO_2 increases anomalously during and in the year after large El Niño events.

Sun et al. (2017) reported that OCO-2 represents a major advance in remote sensing Solar Induced Fluorescence (SIF) with satellite observations. Analyses suggest that SIF is a powerful proxy for Gross Primary Production (GPP) at multiple spatiotemporal scales and that high-quality satellite SIF is of central importance to studying terrestrial ecosystems and the carbon cycle. OCO-2 SIF characteristics illustrate the mechanistic connections between SIF and GPP. They showed that when OCO-2 data are compared with GPP from flux tower measurements, they were well matched in spatial scale, they correlation coefficients range from 0.89 to 0.99, with similar slopes for three different terrestrial biomes. Earlier studies that used sparse data sets were interpolated over time, and indicated biome specific linear relationships through a transect of temperate deciduous forests, crops, and urban areas. Empirical orthogonal function (EOF) analyses on OCO-2 SIF and available GPP products show highly consistent spatiotemporal correspondence in their leading EOF modes across the globe, suggesting that SIF and GPP are governed by similar dynamics and controlled by similar environmental and biological conditions.

Chatterjee et al. (2017) used OCO-2 XCO_2 observations to study the temporal evolution of XCO_2 anomalies over the tropical Pacific Ocean. Using a combination of data from

OCO-2, the TAO (Tropical Atmosphere Ocean) moored buoy array network and MOPITT, they identified two distinct phases in the response of atmospheric CO_2—an early response driven by reduction in CO_2 outgassing from the tropical Pacific Ocean followed by a lagged and much larger response driven by increased fluxes from the tropical land. Over South America, dry conditions reduced GPP, resulting in a net increase in the flux of carbon to the atmosphere. Over Africa, higher atmospheric temperatures drove increased respiration (R_{eco}) but near-normal GPP, increasing carbon flux to the atmosphere. Southeast Asia experienced higher temperatures and dry conditions, increased vulnerability to fire from land use, and increased emissions of CO_2.

Liu et al. (2017) reported that 2015-16 data from Mauna Loa Observatory and OCO-2 had the largest annual increase of CO_2 (about 3 ppm) since measurements began in the 1950s, even though human emissions were roughly the same as the preceding year. OCO-2 data showed that tropical continents were the primary source of that record increase of carbon dioxide. This heat and drought of the 2015-2016 El Niño had distinctly different impacts on Africa, South America and Southeast Asia, each with different implications for these forests' ability to function as a carbon sink. Tropical South America, including the Amazon rainforest, experienced the driest conditions in 30 years. Trees went dormant or died, reducing photosynthesis and leaving more carbon in the atmosphere. African rainforests endured hotter-than-normal temperatures. Decomposition of dead trees increased, releasing more carbon. In Southeast Asia, drought increased the size and duration of peat and forest fires, releasing more carbon to the atmosphere. This research combined OCO-2 data with other satellite data sets including precipitation and temperature and showed that while carbon is generally released to the atmosphere from land during El Niño years, the processes governing that release varies with by ecosystem.

Schwander et al. (2017) investigated how well can OCO-2 XCO_2 measurements quantify localized increases in XCO_2. They reported that in the Los Angeles region, differences of ~6 ppm were seen from a single orbit of data. The overall statistics show that difference of 1 ppm can be quantified from the data. This study also noted that a volcanic plume was also quantified (Mt. Yasur). The OCO-2 data to date have demonstrated the capability to identify and quantify emissions hot spots from space-based measurements.