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-18-1:</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 on their impacts on climate and air quality. In particular, ACFA helped 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 2018 financial year are highlighted below.

<u>*Aerosol and cloud radiative effects research*</u>

Aerosols have a potentially large effect on climate, particularly through their interactions with clouds. The magnitude of this effect, however, 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 recently observed global changes, as well as being able to better predict the future climate.

Radiative interactions between aerosols and clouds and the importance of cloud height

A-train data were extensively used in the 2018 reporting year. Together with models, they contributed substantially to studies on the very important, poorly understood, and complex aerosol and cloud radiative interactions. Using Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation satellite (CALIPSO) data, Adebiyi et al. (2018) found that these interactions strongly depend on the relative altitude of clouds and smoke layers in the southeast Atlantic. Rajapakshe et al. (2017) reported that from June to October, low-level clouds in the southeast Atlantic often underlie seasonal aerosol layers transported from the African continent. Two seasons of observations from NASA's Cloud-Aerosol Transport System (CATS) on the International Space Station (ISS) revealed that the bottom of the above-cloud aerosols layer is much lower than previously estimated based on CALIPSO observations. CATS data were also used by Noel et al. (2018) to document, for the first time, the diurnal cycle of detailed vertical profiles of cloud fraction. The unique precessing orbit of the ISS reveals diurnal characteristics of clouds that have not previously been observed from spaceborne platforms. The diurnal variability of cloud profiles revealed by CATS strongly suggests that CALIPSO measurements document the daily extremes of the cloud fraction profiles over ocean and are more representative of daily averages over land. Thanks to CATS's detection sensitivity, McGill at al. (2018) provided observational evidence in support of long-held theories of aerosol transport from the African subcontinent over the remote Indian Ocean and as far downstream as Australia. Further, Vaillant de Guélis et al. (2017) assessed the contribution of clouds to the longwave radiation budget at the top of the atmosphere. They showed that integrated CALIPSO profile data compare very well with directly measured longwave cloud radiative effects by the Clouds and the Earth's Radiant Energy System (CERES) instrument. However, the lidar also accurately observes cloud cover and altitude, which allows partition of the derived longwave cloud radiative effects into variations due to changes in cloud amount and cloud altitude. Vaillant de Guélis et al. (2017) also studied the relative influences from opaque, and from semi-transparent, clouds and found the cloud amount to be the primary control on longwave cloud radiative effects in the tropics over the 2008-2015 period. This study points toward the possibility of developing an accurate long-term record of global longwave cloud radiative effects if lidar data continue to be available, such as by the two ESA missions ADM-Aeolus and EarthCARE, as well as by the future observing system addressing the "Aerosols" Designated Observable recommendation by the Decadal Survey (2017).

Cooling effect of dust aerosols quantified
Song et al. (2018) integrated recent aircraft measurements of dust microphysical and optical properties, such as Aerosol Optical Depth (AOD), with satellite retrievals of aerosol and radiative fluxes to quantify the dust direct radiative effects (DRE) on the shortwave (SW) and longwave (LW) radiation at both the top of atmosphere (TOA) and surface in the tropical North Atlantic during summer months. They found a diurnal mean dust DRE-SW efficiency of –-28 W/m^2/AOD at TOA and – 82 W/m^2/AOD at surface. The corresponding TOA and surface DRE on SW in the region is approximately –-10 W/m^2 and –-26 W/m^2, respectively, of which ~30% is canceled out by the positive DRE on LW. This yields a net DRE of about –-6.9 W/m^2 and –-18.3 W/m^2 at TOA and surface, respectively. This study suggests that the LW flux contains useful information of dust particle size, which could be used together with SW observation to achieve more holistic understanding of the dust radiative effect.

Climate change indicators of regional aerosol optical properties
Sullivan et al. (2017) defined aerosol properties (AOD, Angstrom Exponent, Single Scattering Albedo) that could be used as climate indicators within the National Climate Assessment. The authors developed statistical techniques to describe how these aerosol climate indicators vary in space and time over different regions. These statistics were applied to the MERRA-2 re-analysis (which includes assimilation of satellite-retrieved aerosol products). For most regions, the trend is toward lower aerosol burdens (decreased mean and extreme AOD), relatively more absorbing particles (lower Single Scattering Albedo) and relatively smaller diameter particles.

Enhanced aerosols overserved near clouds may be an artifact due to scattered light
To study aerosols close to clouds, Spencer et al. (2018) adapted the Dark-Target aerosol retrieval algorithm used for MODIS with lower spatial resolution (~500 m) to data produced by the airborne enhanced-MODIS Airborne Simulator (eMAS) with higher

spatial resolution (~50 m). They apply the classic Dark-Target aerosol retrieval technique to observations collected over the southeastern United States during late summer 2013 during the $SEAC_4RS$ experiment. The resulting product suggests that total AOD can be greatly enhanced near clouds. When comparing the retrieved AOD to other datasets (MODIS, Cloud Physics Lidar, AERONET), they found the enhanced AOD near clouds is only partially observed in other datasets, suggesting it may be primarily an adjacency effect where light scattered from bright clouds is scattered into the field of view of the sensor.

Liquid water clouds are found to control the surface radiation budget in the Arctic
Morrison et al. (2018) investigated influences of sea ice cover on Arctic clouds using Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) profile data from CALIPSO. Eight years of data are used, partitioning cloud observations into those over sea ice and those over open water. Liquid water clouds are found to control the surface radiation budget in the Arctic and therefore perhaps influence the formation and melting of sea ice in fall and summer, respectively. No cloud response to sea ice variability is seen in summer. In other seasons, however, more clouds are seen over open water than over sea ice. The lack of a cloud response during summer implies that clouds provide neither a positive nor a negative feedback during the season of peak Arctic sea ice loss.

Challenge to observe major aerosol pollution events in the China/Korea/Japan
Analysis by Eck at al. (2018) of sun photometer measured and satellite retrieved AOD has shown major aerosol pollution events in the China/Korea/Japan region are often observed to be associated with significant cloud cover. Thus, remote sensing of these events is difficult. Possible physical mechanisms for these high AOD events include a combination of aerosol humidification, cloud processing, and meteorological covariation with atmospheric stability and convergence. The newly improved Aerosol Robotic Network (AERONET) AOD data product now allows for unprecedented ability to monitor these extreme pollution events. Studying the 2012 winter-summer period, comparisons of AERONET daily average fine mode AOD data showed that Moderate Resolution Imaging Spectroradiometer (MODIS) satellite remote sensing of AOD often did not retrieve and/or identify some of the highest fine mode AOD events in this region. Also, compared to models that include data assimilation of satellite retrieved AOD, the AERONET fine mode AOD was significantly higher in magnitude, particularly for the highest AOD events often associated with significant cloudiness.

Impact of a potential gap in spaceborne Lidar data
The community is preparing for a gap in the global lidar satellite data record established by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) instrument. A gap could appear after NASA's current CALIPSO and ESA's ADM-Aeolus (launch in August 2018) instruments cease operations. The next lidar in space will be on ESA's EarthCARE mission, which is currently scheduled to launch in 2021. The next generation of a NASA lidar in space, as recommended in the Decadal Survey, will likely not produce data before the mid 2020ies. A model-based study by Chepfer et al. (2018) reports that short gaps of about two years would likely not have significant impact on the capability to constrain the cloud feedback if all the space lidars were

intercalibrated. However, any intercalibration shift between successive lidar missions would delay the capability to constrain the cloud feedback mechanisms.

Regional Intensification of the Tropical Hydrological Cycle During ENSO
Stephens et al. (2018) pieced together several independent measurements collected over multiple decades to reveal a strong, positive feedback on tropical convection associated with the short-term climate variations of the El Niño/Southern Oscillation (ENSO). The feedback is a result of coupled dynamical-radiative processes that produce intensification of the tropical hydrological cycle by more than twice than what is expected from the Clausius-Clapeyron response alone. The study concludes that moist regions precipitate more than dry and the resultant cloud fields interact with radiation in a manner that reinforces the circulation pattern that sets the moist/dry locations. This supports the widely held paradigm of a warming world: “wet gets wetter and dry drier.” For example, the Inter-Tropical Convergence Zone (ITCZ), where deep tropical convection is organized into broad convective zones, is shown by Stephens et al. (2018) to undergo variability that is often used to test ideas thought to be relevant to climate change.

Seasonal variability of warm boundary layer cloud and precipitation in the Southern Ocean
Many climate models underestimate cloud albedo in the Southern Ocean causing global scale biases in our understanding of the earth’s radiation budget. A recent study by Mace et al. (2018) found correlations between biogenically enhanced cloud condensation nuclei concentrations and cloud droplet number concentrations derived from passive satellite data, suggesting marine biological activity influences cloud properties and thus albedo. This study also found a seasonality in the cloud droplet number concentration and the propensity of clouds to rain in a manner physically consistent with the hypothesis that biogenic activity within the ocean can influence cloud and precipitation properties. These processes are only crudely represented in current models.

Unusually deep wintertime cirrus clouds observed over the Alaskan Subartic
Campbell et al. (2018) reported observations of unusually deep wintertime cirrus clouds exceeding 13 km above mean sea level at the NASA Micro-Pulse Lidar Network (MPLNET) site in Fairbanks, Alaska. Such occurrences are quite rare, both regionally and seasonally, based on a 2006–2015 climatology developed from CALIPSO measurements. However, polar meteorology is undergoing significant change and cloud macrophysical as well as occurrence characteristics may prove important to predict potential changes in the polar climate.

Cirrus cloud radiative forcing observations are found consistent with theory
Daytime TOA cirrus cloud radiative forcing is estimated by Lolli et al. (2017) for cirrus clouds observed in 2010 and 2011 at the Singapore MPLNET site. Estimates derived for both overland and overwater to simulate conditions over the broader Maritime Continent archipelago of Southeast Asia. The results are consistent with an open hypothesis of a meridional hemispheric gradient in cirrus cloud daytime TOA radiative forcing globally, varying from positive near the equator to, presumably, negative approaching the poles. The work by Lolli et al. (2017) helps further expand upon the paradigm by

conceptualizing differences zonally between overland and overwater forcing that differ significantly. More global oceans are likely be subject to negative daytime TOA cirrus cloud radiative forcing than previously thought.

Strong positive low cloud feedback observed

Satellite measurements of Sea Surface Temperature (SST) and low marine cloud coverage correlations help improve understanding of cloud responses to interannual SST anomaly responses (Interdecadal Pacific Oscillation and the Atlantic Multidecadal Oscillation) and inform future climate feedbacks. Yuan et al. (2018) suggests a strong and positive local low cloud feedback due to observational low cloud fraction responses to SST anomalies.

Air quality research

Air pollution from ozone and other trace gases in the boundary layer affects health and welfare significantly. 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 using outdoor monitors across the US and in some major cities around the globe. Such data are temporally continuous, but lack in 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.

Volatile chemical products emerging as largest petrochemical source of urban organic emissions

Transport-derived emissions of volatile organic compounds (VOCs) have decreased owing to stricter controls on air pollution. This means that the relative importance of chemicals in pesticides, coatings, printing inks, adhesives, cleaning agents, and personal care products has increased. McDonald et al. (2018) show that these volatile chemical products now contribute fully one-half of emitted VOCs in 33 industrialized cities. Thus, the focus of efforts to mitigate ozone formation and toxic chemical burdens needs to be adjusted.

Air quality controls have helped in reducing PM2.5 exposure

New techniques applied by Meng et al. (2018) to the recently improved Multi-angle Imaging SpectroRadiometer (MISR) aerosol data product have shown predicted concentrations of $PM_{2.5}$ capture large regional patterns. This study also identified fine gradients of sulfate, nitrate, organic carbon and elemental carbon $PM_{2.5}$ aerosol species in urban areas of Los Angeles and the Central Valley, California, between 2001 and 2015. Those results suggest air quality controls produced a positive benefit by reducing $PM_{2.5}$ exposure. The upcoming NASA Earth Venture instrument Multi-Angle Imager for Aerosols (MAIA) will provide more detailed data to extend similar analysis in multiple large cities with air pollution challenges around the globe.

Impact of California fires on Air Quality: The role of a low-cost sensor network and satellite observations

Gupta et al. (2018) analyzed $PM_{2.5}$ observations from a network of low-cost (<$200) sensors deployed throughout the Los Angeles area. Data from these sensors have been compared with reference-grade quality sensors to show expected performance with moderate uncertainties. These $PM_{2.5}$ measurements are then compared with aerosol products from the MODIS sensors, specifically for a smoke event during October 2017, leading to useful statistical models to convert AOD to $PM_{2.5}$ at finer spatial resolutions.

Surface level ozone forming pollutants have not continued to decline as expected

Jiang at et. (2018) analyzed satellite NO_2 and CO measurements along with ground-based air quality and emissions. The authors found ambient levels of pollutants contributing to the formation of surface level ozone, inconsistent with a fairly steady decline expected based on US EPA emissions inventories. They also showed these differences could be explained by a shifting contribution of different sectors, such as (i) growing relative contributions of industrial, area, and off-road sources, (ii) decreasing relative contributions of on-road gasoline, and (iii) slower than expected decreases in on-road diesel emissions.

Tropospheric ozone trends remain difficult to reconcile

Gaudel et al (2018) performed an extensive examination of tropospheric ozone trends drawing from in-situ data (IONS and SHADOZ) and mostly tropospheric ozone satellite products, including OMI/MLS, TES, IASI, SCIAMACHY, etc. These authors determined trends in free-tropospheric mean mixing ratio or column amounts from 1995-2015, The results appear to show ozone in many mid-latitude and some tropical regions has increased. However, the uncertainty in all the individual methods is substantial and even the sign of change diverges among some of the data. A landmark study pointing out where improvements in our satellite retrieval estimates of tropospheric ozone is needed.

Surface ozone (O_3) estimation using carbon monoxide (CO) and formaldehyde (CH_2O) measurements

Strong correlations of O_3--CH_2O, O_3--CO and CO--CH_2O were observed during the Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) aircraft experiment in July 2011 over the Washington-Baltimore area. Cheng et al. (2018) found that biogenic isoprene oxidation makes the largest contribution to the regression slope of O_3--CH_2O across much of the eastern US, providing a good indicator for O_3 enhanced by biogenic isoprene oxidation. In contrast, the regression slope of O_3--CO is controlled by both anthropogenic and biogenic emissions. The analysis provides the basis for using high-quality geostationary satellites with UV, thermal infrared, or near infrared instruments for observing CH_2O and CO to improve surface O_3 distribution monitoring.

Tropospheric greenhouse and other trace gas research

The dominant factor in the radiative forcing of climate is the increasing concentration of various greenhouse gases in the atmosphere. Some greenhouse gases, for example, CO_2, methane (CH_4) and nitrous oxide (N_2O), persist in the atmosphere over time scales of a decade to centuries. Several recent studies regarding the emissions of these species in the atmosphere are highlighted here. These studies involve data from the NASA OCO-2 mission as well as OMI and TES on Aura, as well as other key sources of data like AGAGE.

Fossil fuel carbon emissions in California and the Boston urban area
A few cities and states are taking a leading role in US efforts to reduce greenhouse gas emissions. New independent and traceable methods for the estimation of fossil fuel emissions are needed to assess progress in regions where efforts for reducing greenhouse gas emissions are taken, and in data-poor regions. A study by Graven et al. (2018) used advanced atmospheric carbon monitoring that included isotope measurements to provide estimates of fossil fuel emissions to the atmosphere in California for three months in 2014-2015. The study results are found to be consistent with reported fossil fuel emissions by the California Air Resources Board. On the other end of the continent, Boston has adopted reduction targets for anthropogenic and biogenic carbon emissions that include reducing emissions 25% below 2005 levels by 2020, and total carbon neutrality by 2050. Sergent et al. (2018) used a model to quantify emissions in the Boston urban area, which is generating a flux greater than 18% of the 2005 level. They assessed the emissions with a "bottom-up" approach that derives fossil fuel use from various sources combined with biological flux models and the carbon content of the fuel and a "top-down" approach that quantifies emissions based on greenhouse gas emissions measured in the atmosphere.

Impact of uncertainties in the wind field in estimates of CO_2 fluxes
A study by Basu et al. (2018) explores the impact of uncertainties in the wind field in estimates of CO_2 fluxes derived from space based XCO_2 measurements, like those from the Orbiting Carbon Observatory 2 (OCO-2) Mission. Atmospheric transport uncertainties were derived from comparisons of 5 different transport models. They found in the absence of in situ CO_2 and - XCO_2, OCO-2 estimates of regional-scale terrestrial fluxes over land can be more robust to transport model differences than corresponding in situ CO_2 inversions due to increased sampling by the space-based measurements. The impact of transport uncertainties on CO_2 fluxes is similar in northern temperate regions and in the tropics. However, spatial and temporal differences in sampling, including between OCO-2 land and ocean soundings, coupled with imperfect transport, can produce differences in flux estimates larger than flux uncertainties due to transport model differences alone. These results can be used to estimate the robustness of conclusions drawn from OCO-2 and in situ CO_2 flux inversions.

Quantifying CO_2 emissions from individual power plants from space
In order to better manage anthropogenic CO_2 emissions, improved methods of quantifying emissions are needed at spatial scales from the national level down to the facility level. Although the OCO-2 satellite was not designed for monitoring power plant emissions, a study by Nassar et al. (2017) shows in some cases, CO_2 observations from OCO-2 can be used to quantify daily CO_2 emissions from individual middle- to large-sized coal power plants by fitting the data to plume model simulations. Emission estimates for U.S. power plants are within 1–17% of reported daily emission values,

enabling application of the approach to international sites that lack detailed emission information. This affirms a constellation of future CO_2 imaging satellites, optimized for point sources, could monitor emissions from individual power plants to support the implementation of climate policies.

More insights to the complex methane trends
According to a study by Worden et al. (2017) in *Nature*, Methane emissions from fires, identified using Measurement of Pollution in the Troposphere (MOPITT) and Tropospheric Emission Spectrometer (TES) carbon monoxide and methane measurements, have been decreasing since the early 2000s due to a global decrease in tropical fires. The magnitude of this trend is nearly twice as much as expected from prior estimates. The decrease can help to explain overall methane trends and the previously conflicting increases seen from fossil fuel and wetland sources for methane.

Why blowing snow is important to the "Bromine explosion" during Arctic spring
Bromine radicals (Br + BrO) are important atmospheric species owing to their ability to catalytically destroy ozone as well as their potential impacts on the oxidative pathways of many trace gases. Recent space-based observations have reported rapid enhancements of tropospheric BrO over large areas (so called "BrO explosions") connected to near-surface ozone depletion occurring in polar spring. Choi et al. (2018) use tropospheric column BrO retrievals from the Ozone Monitoring Instrument (OMI) in conjunction with the Goddard Earth Observing System Version 5 (GEOS-5) data assimilation system to conclude the sea salt aerosol generated by blowing snow is an important factor in the formation of the "BrO explosion" observed from space during Arctic spring.

OMI NO_2 long-term trends in the United States reported using improved OMI retrievals
Tropospheric NO_2 retrievals from OMI have led to many influential studies on the relationships between socioeconomic activities and NOx emissions. However, the current OMI tropospheric NO_2 retrievals are not designed for analyzing multi-year tropospheric NO_2 trends. A study by Zhang R. et al. (2018) used improved OMI retrievals for trend analysis by removing the ocean trend, using MODIS albedo data in air mass factor calculation, and applying a lightning flash filter to exclude lightning affected OMI NO_2 retrievals. The study confirms a close agreement (within 0.3% yr^{-1}) between in situ and the improved OMI-based NO_2 regional annual relative trends. Further, Zhang R. et al. (2018) concludes that the optimized OMI-based NO_2 regional annual relative trend in the US is -2.0%±0.3 yr^{-1} in West (-2.0%±0.3 yr^{-1}), -1.8%±0.4 yr^{-1} in the Midwest, -3.1%±0.5 yr^{-1} in the Northeast, and -0.9%±0.3 yr^{-1} in the South. Overall, the OMI-based annual mean trend over the contiguous United States is -1.5%±0.2 yr^{-1}. This is a factor of 2 lower than that of EPA's Air Quality System (AQS) ambient air pollution in situ data (-3.9%±0.4 yr^{-1}). This difference is assumed mainly due to the fact that the locations of AQS sites are concentrated in urban and suburban regions.

Monitoring Global Tropospheric OH Concentrations using Satellite Observations of Atmospheric Methane
A comprehensive approach to carbon monitoring includes both measurement of stocks,

and quantification of the processes affecting changes in stocks. Zhang Y. et al. (2018) found recent advances in the ability to monitor atmospheric methane (CH_4) from space can also be used to advance the monitoring of hydroxyl radical (OH) - the main tropospheric oxidant and atmospheric sink for methane. The study finds satellite observations should be able to constrain the global tropospheric OH concentrations with an accuracy of a few percent. Retrievals from space can thus separate contributions from methane emissions and OH concentrations to the methane budget and its trend. It further finds satellite methane observations can constrain the interhemispheric difference in OH. The main limitation to the accuracy is the uncertainty in the spatial and seasonal distribution of OH.

Upper atmospheric and ozone depletion research

Stratospheric composition remains an area of interest 32 years after the discovery of the Antarctic ozone hole and 31 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.

The return of ozone depleting substances due to increased emissions in East Asia
In general, the chemicals regulated by the Montreal Protocol showed rising concentrations and inferred emissions before regulation, and decreasing inferred emissions, and ultimately concentrations, after regulation. For example, ozone depleting chlorofluorocarbons (CFC) have decreased dramatically in the 1990s as a consequence of the Montreal Protocol. However, the monitoring of those substances, such as through the Advanced Global Atmospheric Gases Experiment (AGAGE) network, has found recent increases in global emissions of some CFCs. For example, CFC-13 increased monotonically from its first appearance in the atmosphere in the late 1950s. Its growth rate has decreased since the mid-1980s but has remained at a surprisingly high level since 2000, resulting in a continuing growth of CFC-13 in the atmosphere. The story for CFC-114 and CFC-115 is comparable. However, the mean yearly emissions of CFC-115 have recently (2015-2016) doubled as compared to the 2007-2010 minimum. Observations from the Korean AGAGE site at Gosan reported in Vollmer at al. (2018) show significant emissions for CFC-114 and CFC-115, suggesting that a large fraction of their global emissions currently occur in northeastern Asia and more specifically on the Chinese mainland. Similarly, Simmonds et al. (2018) reported that the trifluoromethane (HFC-23, CHF_3), a potent greenhouse gas largely emitted to the atmosphere as a by-product of the production of the hydrochlorofluorocarbon HCFC-22 ($CHClF_2$), global mole traction has increased by 28% between 2009 and 2016. In the same time span, HCFC-22 has increased by 19%. Some of the HFC-23 emissions remain as a consequence of incomplete mitigation from all HCFC-22 production. The cumulative HFC-23 emissions led to an increase in radiative forcing of 1.0 mW/m_2 over the same period. The majority of the increase in global HFC-23 emissions since 2010 is attributed to a delay in the adoption of mitigation technologies, predominantly in China and East Asia.

Stratospheric ozone recovers in the upper but declines in the lower stratosphere
Conclusive verification that stratospheric ozone destruction is lessening as expected in

response to international controls on anthropogenic ozone-depleting substances (ODSs) enacted under the Montreal Protocol is one of today's atmospheric science imperatives. The length and quality of the observational record are just now approaching those required for the detection of statistically significant ozone trends in the post-peak ODS period, and early signs of ozone recovery are beginning to emerge in some regions. For example, the long-term record of ozone profile observations from the Aura Microwave Limb Sounder (MLS) and other sensors shows a statistically significant increase in the amount of ozone in the upper stratosphere (~35–50 km) since about the year 2000 (Steinbrecht et al., 2017). In other regions, however, the magnitude and even the sign of the trend in ozone remain unclear. Ball et al. (2018) confirmed the recovery of ozone in the upper stratosphere but presented evidence of a continuing decline in lower stratospheric global (60N–60S) ozone. They applied a dynamical linear modeling regression approach to analyze several homogenized and bias-corrected total column and partial column ozone data sets, some of which are based primarily on Aura MLS measurements, over the period 1998–2016. They found a highly probable decrease in lower stratospheric ozone that was not simulated by two state-of-the-art chemistry-climate models (CCMs). They posited several explanations for the observed ongoing decrease in lower stratospheric ozone and the failure of the models to reproduce it, including transport-related issues and additional but unaccounted for ozone destruction by increasing halogenated very short-lived substances. They further suggested that the lack of significant trends in observed total column ozone may have been brought about by increasing tropospheric ozone (coupled with the recovery in the upper stratosphere) that offset the negative trend in the lower stratosphere.

Subsequently, Chipperfield et al. (2018) compared results from a state-of-the-art chemical transport model (CTM) to some of the same datasets used by Ball et al. (2018) but updated through the end of 2017. They showed that, following a negative anomaly in 2016, lower stratospheric ozone at extrapolar latitudes increased sharply in 2017. Thus, including one additional year in the observational time series altered the picture substantially, from one of a continuing decreasing trend to one of strong interannual variability. Furthermore, unlike in the case of the nudged Community Climate Models, the large variations in observed ozone, which Chipperfield et al. (2018) ascribed mainly to atmospheric dynamics, were captured well throughout the stratosphere by the CTM directly forced by meteorological reanalyses. Based on their model sensitivity experiments, Chipperfield et al. (2018) concluded changes in very short-lived substances made only small contributions to recent lower stratospheric ozone variations, and they also noted that positive tropospheric ozone trends are not needed to reconcile their calculated partial stratospheric and total column ozone abundances.

Flux of stratospheric ozone into the troposphere is larger than anticipated
Observations from the MLS and TES instruments on Aura were central to a recent study of stratosphere-to-troposphere transport (STT) associated with extratropical cyclones. Jaeglé et al. (2017), using a multiyear-composite approach to build a climatology from more than 15,000 such cyclones, estimated that transport of ozone in the "dry intrusion" airstream region of the cyclones accounts for an estimated 42% (+/-20%) of the Northern Hemisphere STT ozone flux, contributing an estimated 119 Tg O_3/yr to the troposphere.

The study also showed that state-of-the-art models underestimate this flux by a factor of two.

Deep convection may not play a major role in hydrating the stratosphere
Variations in stratospheric water vapor are known to have a significant impact on surface climate, yet the processes controlling the long-term evolution of stratospheric humidity remain incompletely understood. Schoeberl et al. (2018) used Aura MLS water vapor and CALIPSO cloud ice measurements, in conjunction with a Lagrangian process model, to quantify the contributions of various process, including gravity waves, supersaturation, and deep convection (as diagnosed from both meteorological analyses and direct satellite observations), to the stratospheric water vapor budget. In agreement with previous analyses that indicated a potential contribution from direct injection of ice by overshooting (deep) convection, this study finds a small role for convection in affecting stratospheric humidity. The key factor is that convection rarely penetrates the tropopause 'cold trap', which largely controls stratospheric water vapor.

El Niño's impact on record high atmospheric Hydrogen Cyanide mixing ratios
El Niño events are known to have wide-ranging impacts on the Earth system. Atmospheric Hydrogen Cyanide (HCN) originates almost entirely from biomass burning, with peat burning generating far more HCN than any other fire type. Aura MLS observations showed (Pumphrey et al., 2018) a dramatic enhancement in lower stratospheric HCN over the tropical Indian and Western Pacific oceans during the 2015-2016 El Niño. HCN doubled as compared to the typical background amounts. This period saw intense peat fires in Indonesia in response to the El Niño-induced drought.

Airborne activities

Programmatic and Earth Venture class Suborbital missions continued to be important contribution of ACFA to supplement current, and prepare for, future spaceborne 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 below. More information on NASA's airborne missions can be found here: https://espo.nasa.gov/content/ESPO_Missions or following further links given below.

ObseRvations of Aerosols above CLouds and their intEractionS (ORACLES)
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. In 2017, the ORACLES team successfully completed its second of three deployments out of São Tomé. The team is currently preparing for their third deployment in fall 2018. First science results from the 2016 deployment are being published. For example, Xu et al. (2018) illustrates the potential of the ORACLES (EVS-2) data set to test and improve the joint aerosol and cloud retrievals using an imaging polarimeter, with potentially significant implications for future satellite deployment of such an instrument. The paper shows good agreement to independent assessments of cloud optical depth and above-cloud aerosol optical depth. Diamond et al. (2018) describes ORACLES measurements in the SE Atlantic that show good correlation for cloud drop number concentration and smoke below cloud but weak correlation with

smoke above cloud. Their findings illustrate that the history of entrainment (characteristic timescale of ~3 days) is as important as instantaneous smoke contact for observed cloud properties.

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 towards 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 Strode at al. (2018) provides insights from airborne and satellite observations and modeling (GEOS-5) by forecasting CO and aerosols on a global scale for the first Atom deployment in August 2016. They found for most flights that the dominant contribution to total CO is from non-biomass burning sources, which include both fossil fuels and biofuels and oxidation of hydrocarbons including methane. An exception to this is in the lower troposphere of the tropical Atlantic, where biomass burning from Africa makes the largest contribution, reaching high levels in some locations. The non-biomass burning source includes a large fraction from Asia for flights over the North Pacific and from both Asia and North America for the North Atlantic and North American flights, while other regions dominate in the Southern Hemisphere. Plumes of elevated CO from both biomass burning and non-biomass burning sources led to observations of enhanced CO during ATom in 2016. MOPITT, MODIS, and MLS satellite observations from 2000 to 2016 suggest that the high values of CO and aerosols from biomass burning encountered during the tropical Atlantic portions of ATom may have been especially pronounced during ATom in 2016.
More information: https://espo.nasa.gov/atom/content/ATom

Atmospheric Carbon and Transport – America (ACT-America) Mission
ACT-America conducts five airborne campaigns across three regions in the eastern US to study the transport and fluxes of atmospheric carbon dioxide and methane. The study enables more accurate and precise estimates of the sources and sinks of these gases. Better estimates of greenhouse gas sources and sinks are needed for climate management and for prediction of future climate. Díaz-Isaac et al. (2018) suggests that atmospheric transport model studies have likely underestimated CO_2 concentration if they were solely focusing on the atmospheric boundary layer. The study used an ensemble of Weather Research and Forecast (WRF) models to examine the impact of parameterizations of atmospheric physics on both the simulated meteorology and CO_2 concentrations. The results show that multiple physics parameterizations, including land surface fluxes, the atmospheric boundary layer, and cumulus clouds, in addition to the choice of global reanalysis product, have a significant impact on the random error in CO_2 concentration.

In addition, the ensemble overestimated boundary layer depth in the western portions of the region, and overestimated wind speeds in the eastern portion of the region. No ensemble member was free from biases across the simulation region. This suggests that any single model configuration will suffer from some degree of bias in its simulation of atmospheric transport, and that care must be taken to create an unbiased atmospheric transport ensemble.
More information: https://act-america.larc.nasa.gov

Overview of the Airborne Tropical TRopopause EXperiment (ATTREX)
ATTREX (Jensen et al. 2016) was a series of airborne campaigns between 2011 and 2015 focused on understanding physical processes in the Tropical Tropopause Layer (TTL) and their role in atmospheric chemistry and climate. ATTREX used the NASA Global Hawk Unmanned Air System to make in situ and remote-sensing measurements spanning the Pacific. A particular ATTREX emphasis was to better understand the dehydration of air as it passes through the cold tropical tropopause region. The ATTREX payload included 12 in situ and remote sensing instruments that measured water vapor, clouds, multiple gaseous tracers (CO, CO_2, CH_4, NMHC, SF_6, CFCs, N_2O), reactive chemical compounds (O_3, BrO, NO_2), meteorological parameters, and radiative fluxes.

As of 2018, the ATTREX dataset contributed to at least 25 papers and is still being actively used by a number of groups to advance our understanding of TTL cloud process, dynamics, transport, and chemical composition, as well as for evaluation and improvement of global models. For example, from ATTREX observations Jensen et al. (2017) suggests that the typically saturated air in the lower tropical tropopause layer (≃14–18 km) over the western Pacific is likely driven by a combination of the frequent occurrence of deep convection and the predominance of rising motion in this region. The nearly constant water vapor mixing ratios in the middle to upper tropical tropopause layer likely results from the combination of slow ascent (resulting in long residence times) and wave-driven temperature variability. Sensitivity tests by Jensen et al (2017) emphasize the strong influence of convective input and vertical motions on tropical tropopause layer relative humidity. Another research example is based on data from ATTREX together with the Coordinated Airborne Studies in the Tropics (CAST) and the Convective Transport of Active Species in the Tropics (CONTRAST) experiment campaigns where Newton et al. (2018) reports that very low ozone concentrations in the boundary layer and low troposphere (~7 ppb) were observed, whereas in the upper troposphere concentrations were generally much higher (>15 ppb). These results are consistent with uplift of almost-unmixed boundary-layer air to the tropical tropopause layer in deep convection. Further, Newton et al. (2018) found lower ozone concentrations in the tropical tropopause layer of the Southern Hemisphere as compared to the Northern Hemisphere. Further evidence of a boundary-layer origin for the uplifted air is provided by the anticorrelation between ozone and halogenated hydrocarbons of marine origin observed in those campaigns.

Korea-United States Air Quality Study (KORUS-AQ)
The KORUS-AQ Science Team continues to make progress on scientific results. After the initial data workshop in 2017, a Rapid Science Synthesis Report (RSSR) was

produced and delivered to South Korea's Ministry of Environment. This document provided early, high-level findings to the Korean government regarding local emissions and their influence on ozone and particulate pollution as well as transboundary influences. In a collaboration between Korean and U.S. scientists, major papers are currently being drafted and submitted soon after a second science team meeting in August 2018. These peer-reviewed results will form the basis for a Final Science Synthesis Report intended for delivery to the Ministry of Environment in early 2019. RSSR report:https://espo.nasa.gov/sites/default/files/documents/KORUS-AQ-ENG.pdf

Aerosol Characterization from Polarimeter and Lidar (ACEPOL)
The ACEPOL campaign performed aerosol and cloud observations over the Western US in October and November 2017. It was a collaborative effort among the NASA ACE pre-formulation study and the CALIPSO project, as well as the Netherlands Institute for Space Research. The acquired data from ACEPOL enable the assessment of proposed instruments capabilities by the ACE pre-formulation study to answer fundamental science questions associated with aerosols, clouds, air quality and global ocean ecosystems. This is very relevant in light of the coming NASA activities related to the implementation of the recommendations by Decadal Survey (2017) on Aerosol and Cloud/Convection/Precipitation designated observables. ACEPOL was featured in this NASA press release:
https://www.nasa.gov/centers/armstrong/features/prototype_space_sensors.html

Clouds, Aerosol, and Monsoon Processes-Philippines Experiment (CAMP2Ex)
In partnership with Philippine research and operational weather communities, NASA will help to better characterize the role of anthropogenic and natural aerosol particles in modulating the frequency and amount of warm and mixed phase precipitation in the vicinity of the Philippines during the Southwest Monsoon. The field campaign in summer 2019 will examine how aerosol particle concentration and composition effect the optical and microphysical properties of shallow cumulous and congests cloud, and how, ultimately, these effects relate to the transition from shallower to deeper convection. It will also study how spatially inhomogeneous and changing aerosol and cloud fields impact three-dimensional heating rates and fluxes, as well as determine the extent to which 3 dimensional effects may feedback into the evolution of the aerosol, cloud, and precipitation fields. And finally, it will determine the meteorological features that are the most influential in regulating the distribution of aerosol particles throughout the regional atmosphere and, ultimately, aerosol lifecycle, and ascertain the extent to which aerosol-cloud interactions studies are confounded and/or modulated by co-varying meteorology. More information: https://espo.nasa.gov/sites/default/files/documents/CAMP2Ex-overview-27NOV2015.pdf

Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ)
Fire is important for many ecosystems, but it also poses costly risks to human health and property. The combination of a warmer and drier climate with population growth and fire-control practices has produced a situation of larger and more frequent fires in the US and Canada. NOAA and NASA are going to conduct FIREX-AQ, a joint field program in summer 2019, to address related burning science questions on fuel emission factors and

estimates, smoke optical properties, as well as plume injection heights, transport, and chemistry.
More information: https://www.esrl.noaa.gov/csd/projects/firex/whitepaper.pdf

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FY 2018 Annual Performance Indicator	FY15	FY16	FY17	FY18
ES-18-1: 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.	Green	Green	Green	Green

Annual Performance Indicator ES-18-3: Demonstrate planned progress in improving the capability to predict weather and extreme weather events.

The Weather Focus Area (WFA; https://science.nasa.gov/earth-science/programs/research-analysis/earth-weather) uses NASA's 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.

Characterizing and Understanding Precipitation Processes

Since the end of TRMM mission, GPM has 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), GPM Microwave Imager (GMI), combined DPR+GMI, and merged satellite estimates. Some of the recent publications related to algorithm development work include: Stocker et al., 2018, Le et al., 2017, Wright et al., 2017, Tan et al., 2017.

Data from GPM have produced several scientific accomplishments in the past year. Using GMI microwave polarimetric signals from the 166 GHz vertical and horizontal channels, Gong and Wu (2017) found that the radiative scattering of frozen particles is highly polarized in the upper troposphere throughout the tropics and mid-latitude jet regions, and hence indicate that the ice particles are horizontally oriented.

Collaboration with the Water and Energy Cycle Focus Area made some of the GPM ground validation activities possible. Ground validation (GV) data have supported a range of studies related to the testing, development, and/or verification of GPM retrieval algorithms and supporting cloud models. These include the physics of, and methods to parameterize, the rain drop size distribution (DSD; e.g., Tokay et al., 2017; Raupach and Berne, 2017), including new observations of small raindrops (< 0.5 mm) and their impact on current approaches to representing the DSD in light rain (Thurai et al., 2017. Measurements of snow water equivalent rate can be found in Moisseev et al. (2017) and von Lerber et al. (2017). GPM's field campaign data have also combined the use of hydrologic modelling and observations to develop "best" estimates of liquid and frozen precipitation accumulation over complex terrain (Cao et al., 2017). Currier et al., 2017 have performed an independent validation of falling snow using OLYMPEX data, It was found that orographic perturbation of the prevailing low-level flow and associated enhancements of the precipitation process were important during OLYMPEX (see also Houze et al., 2017, and Zagrodnik et al., 2017). GPM supported the International Collaborative Experiment – PyeongChang Olympics-Paralympics 2018 (ICE-POP 2018; led by the Korean Meteorological Administration, February-March, 2018). ICE-POP enabled further GPM studies of orographic precipitation processes, and in particular, orographic snow, over regions characterized by large ocean to mountain terrain gradients.

Atmospheric Dynamics

NASA continues to make complete atmospheric profile 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.

Recently, ground-breaking retrieval algorithms for single-footprint, infrared-only retrievals from AIRS L1 data have been developed (Irion et al., 2018; DeSouza-Machado et al., 2018). By including clouds in the retrieval radiative forward model, and not using “cloud-cleared” radiances, the horizontal resolution of AIRS retrievals is improved from ~ 45 km^2 to ~13.5 km^2 (at nadir). The results showed increased horizontal detail in temperature, water vapor and relative humidity structure and compared well with ECMWF reanalyses and coincident radiosonde profiles. In particular, these algorithms are able to retrieve temperature and water vapor in the eye of hurricanes – something not possible with the previous algorithms.

Research utilizing AIRS observations continues to produce new discoveries and to lead to several science investigations related to weather. From atmospheric gravity waves to extreme weather, and from boundary layer studies to improvements in numerical weather prediction, AIRS data continues to play a key role in NASA’s weather science.

The dynamics and thermodynamics of the subtropical marine boundary layer remains poorly understood. Kahn et al. (2017) developed an approach that uses AIRS and other NASA A-train data with the Modern Era Retrospective-Analysis for Research and Applications (MERRA) data to quantify dynamical processes and relationships in the subtropical boundary layer, and to better understand four subtropical oceanic regions that capture transitions from stratocumulus to trade cumulus.

AIRS observations were crucial to investigate the regional intensification of the tropical hydrological cycle during ENSO (Stephens et al., 2018). This paper provides observational evidence for feedbacks that amplify the short-term hydrological response associated with the warm phase of the El Niño-Southern Oscillation. Stephens et al. (2018) show that much larger local changes to cloud (~50%/K) and precipitation (~60%/K) occur than would be expected from the Clausius-Clapeyron relation (~7%/K).

Recent studies continue to demonstrate the usefulness of AIRS observations in weather prediction science and in improving weather forecasts. For example, Christophersen et al. (2018) and Yan-An et al., (2018) use AIRS observations in new ways in order to improve tropical cyclone and typhoon forecasts.

The interplay between weather and atmospheric composition is another area where AIRS observations play a fundamental role. For example, Adame et al. (2018) and Han et al. (2018) investigate the interactions between weather conditions and patterns with trace gases and particulate matter, while Kahn et al. (2018) analyze in detail ice cloud microphysical trends observed by AIRS.

Much progress has been achieved from an applications perspective as well. The U.S. Drought Monitor (USDM) is a weekly map of drought conditions used by policymakers to help determine drought relief allocations and declarations of drought. AIRS humidity products have the capacity to detect meteorological drought up to two months earlier than other drought indicators (e.g. Wardlow et al., 2017). These AIRS products are now being used in the production of the USDM for a probationary period. If utility is demonstrated, they will become part of the regular operational suite of indicators used in the generation of the USDM. Also, AIRS data has great value in confirming volcanic eruptions in remote areas and tracking long-lived ash clouds. The 2017 Earth Science Senior Review noted the importance of AIRS to the FAA and the aviation community by providing sulfur dioxide detection for volcanic plumes, while also noting its use in volcanic ash detection for the NOAA Rapid Update Cycle Rapid Refresh Model. A fully automated rapid response system for sulfur dioxide detection has been developed and will publicly debut in summer 2018. The system triggers on detection of SO2 and dust in the AIRS near real-time data product and provides imagery of SO2, dust and clouds.

Study of Extreme Events

Response to 2017 Major Hurricanes

The hurricane season of 2017 brought several significant storms to the Atlantic basin including three major hurricanes with significant impacts to the United States: Hurricanes Harvey, Irma, and Maria. Hurricane Harvey produced record-setting rainfall and flooding within the Houston metro area. NASA remote sensing including observations from GPM and SMAP captured torrential rains and lingering, high soil moisture content with regions prone to flooding well after the event. GPM's GMI data were specifically mentioned in NOAA’s National Hurricane Center (NHC) hurricane forecasts for Irma and Jose (Skofronick-Jackson, et al., 2018, National Hurricane Center 2017). NASA’s Short-term Prediction Research and Transition (SPoRT) Center operates the NASA Land Information System in collaboration with NASA Goddard, and the integration of NOAA radar-estimated rainfall and atmospheric forcing captured the signature of Harvey's rainfall in southeastern Texas as saturated soils persisted in the weeks and months following the storm. Hurricane Irma's faster movement brought different impacts to Florida, and scientists within NASA's Earth Science programs provided flood mapping, damage mapping, and tracking of the loss or restoration of lights and power through various optical and synthetic aperture radar remote sensing techniques. Many of these same techniques were applied to monitoring the impacts from Hurricane Maria in Puerto Rico and the U.S. Virgin Islands, which experienced the brunt of the storm, and helped to document and monitor the long-lasting and continuing impacts of Maria on Puerto Rico's infrastructure. During Maria, GPM played a critical role in helping NOAA/NWS meteorologists map heavy rainfall and other impacts following damage to and loss of the NOAA/NWS weather radar. Data products generated by GPM and delivered to NWS partners in Puerto Rico by the SPoRT Center were commented by NWS staff for providing crucial information on rainfall amounts during the radar outage, supplemented with other agency information including USGS streamgauges and other satellite products from the GOES series.

Hurricane-Force Ocean Surface Winds
Meissner et al. (2017) demonstrated the capability of NASA's spaceborne Soil Moisture Active Passive (SMAP) radiometer to give accurate estimates of the intensity and radii of hurricane-force winds. The researchers showed how to derive the signal of the wind-induced emissions at L-band frequencies and provided verification of derived wind speeds versus ground truth observations from e.g., buoys and aircraft measurements. SMAP wind speeds were found to be impacted very little by precipitation, even at high rain rates. The scientists also presented examples of SMAP wind speed retrievals for notably intense tropical cyclones that occurred during the 2015 and early 2016 seasons, and compared these with wind fields observed by other space-based missions including the European Space Agency Advanced Scatterometer (ASCAT), the U.S. Navy's multichannel polarimetric radiometer, WindSat, and NASA's Rapid Scatterometer (RapidScat). In these storms and at the satellite footprint scales of 20–50 km, the SMAP radiometer was the only instrument able to observe wind speeds of 55–70 meters per second for all of them.

CYGNSS
In FY17 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. Intensive cal/val activities were conducted during the very active 2017 Atlantic hurricane season using coincident "ground truth" wind speed measurements by the NOAA P-3 hurricane hunter aircraft (specifically, using dropsondes and the Stepped Frequency Microwave Radiometer sensors carried on those aircraft). Results are reported in Gleason et al. 2018, Ruf and Balasubramaniam 2018, and Ruf et al. 2018a.

A number of additional papers have been published in this period to document various aspects of CYGNSS performance. These include improvements in hurricane forecast skill using CYGNSS data (Ciu et al, 2018), improvements in temporal and spatial sampling of tropical convective systems with CYGNSS (Hoover et al., 2018), the ability to measure soil moisture and image flood inundation over land (Chew et al., 2018 and Ruf et al., 2018b), and general relationships between spatial and temporal resolution with CYGNSS.

Convective Process Understanding

Convective Process Experiment (CPEX)
The weather focus area continues to invest in convective process understanding. 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.

CPEX was designed to bring together airborne observations, satellite observations and numerical models in a series of case studies to study and improve our understanding and modeling of convective processes in the tropics. It featured the Doppler Aerosol WiNd lidar (DAWN) and five other remote sensing instruments.

Post mission data studies included comparisons between various instruments to reveal any significant disagreements. One such extensive comparison has been done for the dropsondes and DAWN wind profiles in various situations characterized by the amount and degree of organization of convection. In addition, early evaluation of the use of budget box flight patterns to obtain divergence values over 100km x 100km areas are very encouraging. More than 20 CPEX budget boxes were flown during 16 flights. Areas of differing degrees of convection are now being evaluated. CPEX science team members are working on case studies that integrate satellite, model, and airborne observations to address the three core CPEX objectives. This integration of data sets is being enabled by a CPEX data portal established at JPL https://cpex.jpl.nasa.gov/about.php. More than 20 presentations have been made at conferences and workshops in the past 10 months.

Mesoscale Convective Systems (MCS)
In a blog posted by SPoRT researcher, Case (2018) document impacts of SMAP data assimilation on short-term regional NWP, using the NASA Unified-Weather Research and Forecasting (NU-WRF) modeling framework. One example of forecast improvement occurred on the afternoon of July 13, 2016, when an MCS developed over Missouri and Illinois and quickly moved eastward into Indiana, Michigan, and Ohio and southern Ontario province into the evening. The initial surface soil moisture differences between the SMAP-LIS and SPoRT-LIS show that a distinct drying occurred in the data assimilation output over the Midwest.Meanwhile, a moistening occurred from SMAP DA over portions of Southern Ontario. A similar signal is seen in the deeper soil layers as well. The soil drying signal over the Midwest led to a corresponding increase in 2-m temperatures, decrease in 2-m dew points, and overall decrease in surface convective available potential energy (CAPE). Meanwhile, over southern Ontario, the more moist

soils in the SMAP-LIS initialized run led to an opposite response. These changes to the simulated boundary layer environment led to an overall faster propagation of the MCS across Illinois and Indiana in the SMAP-LIS initialized NU-WRF runs. This faster solution was in better agreement with the observed radar reflectivity at 0000 UTC July 14, 2016.

Global Atmospheric Science Synthesis and Weather Forecast Improvement

Precipitation Processes Improvement in Models
Assimilation of precipitation data into global forecast models continues to be a challenge in global weather modeling. GPM's accurate and frequent measurements of precipitation-affected radiances and instantaneous precipitation rates together with quantitative error characterization have been assimilated into weather forecasting and data assimilation systems to improve 4D reanalysis, with the GPM-CO data being used operationally by the ECMWF (Geer et al., 2017). Assimilating satellite observations from microwave imagers such as GMI in cloudy and precipitating regions provides critical constraints on atmospheric parameters in dynamically sensitive regions and makes significant impacts on weather forecast accuracy. Kim et al. (2017) describe a framework to assimilate GMI all-sky (including cloud and precipitation affected) radiance data using a hybrid 4D-Ensemble Variational (EnsVar) analysis algorithm in the Goddard Earth Observing System version 5 (GEOS-5) that has become part of NASA's Global Modelling and Assimilation Office (GMAO)'s operational forecast system in 2018.

In Holt et al. (2017), gravity waves in the high-resolution (7 km) GEOS-5 Nature Run are evaluated using AIRS data and other satellite observations. The results show that the global patterns in gravity wave amplitude, horizontal wavelength, and propagation direction are realistic compared to observations. However, as in other global models, the amplitudes are weaker and horizontal wavelengths longer than observed.

Operationally, the Joint Center for Satellite Data Assimilation (JCSDA) is currently testing how GMI data improve track forecasting for tropical cyclones (Kirschbaum et al., 2017; Pu and Yu, 2017). The GPM-CO DPR provided (3D) data during overpasses of the 2017 Atlantic Hurricane season including the hot towers associated with Hurricanes Harvey, Irma, Jose, Maria, and Ophelia (https://pmm.nasa.gov/extreme-weather). In addition, GMI data were specifically mentioned in NOAA's National Hurricane Center (NHC) hurricane forecasts for Irma and Jose (National Hurricane Center, 2017). The Navel Research Lab (NRL) Automated Tropical Cyclone Forecasting System (https://www.nrlmry.navy.mil/TC.html) records over 1,000 GMI overpasses annually of cyclones that have been used by forecasters around the globe to monitor tropical cyclone structure.

GPM has contributed to the hydrology and modeling. New work includes: An error model to quantify uncertainty in fine resolution precipitation products for satellite hydrology was proposed by Wright et al. (2018). Climate models, and their parameterizations within the models, can be verified with global precipitation products but care must be taken to address limitations and enforce quality control (Tapiador et al., 2017).

Data Assimilation System Development

With NOAA's commitment to develop a Next Generation Global Prediction System (NGGPS), JCSDA has become a community data assimilation system development center. 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 Annual Operating Plan, which lays out specific tasks for the year, has been developed and GMAO has identified specific areas of developments. For efficiency, activities are organized in a Project structure, with Project Leads working for the JCSDA core team. This year has seen an expansion of the JCSDA core team, which resulted in increased collaboration among JCSDA partners. An efficient tool has been the series of JCSDA code sprints, which GMAO has participated in and benefited from.

Some key accomplishments for this year are presented below:

- Community Radiative Transfer Modeling: a new version of the code (v2.3.0) has been developed and released (Johnson et. al, 2018), which includes software bugfixes, scientific improvements, and new coefficients for an extended list of satellite instruments.
- New and Improved Observations: in coordination with all partners, the JCSDA prepared a synthetic document reporting on the interest, preparation, and level of readiness regarding the operational assimilation of observations from a variety of satellite instruments (Keller et. al, 2018).
- Impact of Observing System: further analysis of results from the international inter-comparison study of Forecast Sensitivity and Observation Impact. Initial steps toward a near-real-time monitoring and diagnostics capability (Hyer et. al. 2018).
- Joint Effort for Data assimilation Integration: following the 'Next-generation data assimilation planning meeting workshop' held in College Park in April 2017 to gather requirements and design feedback from the community, the initial coding phase has begun in August 2017. JCSDA core team members and collaborators have been working collaboratively on a rapid prototype development, thanks to the adoption of modern industry tools and work practices. Multiple models have been interfaced with the new generic JEDI data assimilation code, and in particular the FV3-based GEOS model (as well as FV3-based GFS). A new technology was used to efficiently represent model background error covariances,

regardless of the model grid. This allows the JEDI data assimilation solver to operate directly on the model native grid. Similarly, the interpolation from the model grid to observation locations has been prototyped and is been tested for a subset of observation types. Work lead by GMAO has produced the interfacing of GEOS tangent-linear and adjoint model, which lead to the first 4DVar increments directly on the GEOS cube-sphere grid. The first 'JEDI Academy' was held in Boulder in June 2018 to train early adopters about the software, object-oriented programing and new work practices.

- Sea-ice, Ocean, Coupled Assimilation: development of an early data assimilation prototype for ocean and sea-ice within the JEDI infrastructure.

Application of Knowledge Gained

Kirschbaum and Stanley (2018) developed a Landslide Hazard Assessment for Situational Awareness (LHASA) model to indicate potential landslide activity in near real-time. The combined satellite-based precipitation estimates from the Multisatellite Precipitation Analysis (TMPA) products (based on the TRMM data) and the Integrated MultisatellitE Retrievals (IMERG) (based on the Global Precipitation Measurement (GPM) data) with a landslide susceptibility map were derived from information on slope, geology, road networks, fault zones, and forest loss. When rainfall was considered to be extreme and susceptibility values were moderate to very high, a "nowcast" was issued to indicate the times and places where landslides were more probable. The scientists evaluated the LHASA nowcasts with a Global Landslide Catalog, and found the probability of detection to range from 8% to 60%, depending on the evaluation period, precipitation product used, and the size of the spatial and temporal window considered around each landslide point. LHASA is intended to provide situational awareness of landslide hazards in near real-time, providing a flexible, open-source framework that can be adapted to other spatial and temporal scales based on data availability.

GPM's precipitation products continue to inform scientific studies and benefit societal application activities. These include fire and haze episodes (Shawki et al, 2017), Soil moisture (Lin et al., 2017), and more. A GPM Disease Initiative and Wilson Centre co-sponsored the 2018 Vector-Borne and Water-Related Disease Workshop was held on May 17, 2018, as well as a training webinars, "Using NASA Earth Observations to Predict and Monitor Vector-borne and Water-related Disease," in May and June 2018. Several new animations were developed by SVS for GPM on landslides, cholera, and fires (svs.nasa.gov).

Much progress has been achieved from an applications perspective of AIRS data as well. The U.S. Drought Monitor (USDM) is a weekly map of drought conditions used by policymakers to help determine drought relief allocations and declarations of drought. AIRS humidity products have the capacity to detect meteorological drought up to two months earlier than other drought indicators. These AIRS products are now being used in the production of the USDM for a probationary period. If utility is demonstrated, they will become part of the regular operational suite of indicators used in the generation of the USDM. Also, AIRS data has great value in confirming volcanic eruptions in remote areas and tracking long-lived ash clouds. The 2017 Earth Science Senior Review noted the importance of AIRS to the FAA and the aviation community by providing sulfur dioxide detection for volcanic plumes, while also noting its use in volcanic ash detection for the NOAA Rapid Update Cycle Rapid Refresh Model. A fully automated rapid response system for sulfur dioxide detection has been developed, to debut in summer 2018. The system triggers on detection of SO2 and dust in the AIRS near real-time data product and provides imagery of SO2, dust and clouds.

Short-term Weather Prediction and Transition to Operations

NASA's SPoRT Center (https://weather.msfc.nasa.gov/sport/) is an end-to-end R2O/O2R activity focused on improving short-term weather forecasts through the use of unique high-resolution, multispectral observations from NASA and NOAA satellites, nowcasting tools, and advanced modeling and data assimilation techniques. SPoRT partners with universities and other government agencies to develop new products, which are transitioned to applicable end user decision support systems. Recent advancements in product development and data dissemination, modeling and data assimilation, product applications in various decision support systems, and transition, training and assessment activities have significantly helped to improve operational weather forecasts and in the more efficient detection, monitoring, and community response to natural disasters.

- SPoRT has completed assimilation 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 (Blankenship et al. 2016 and Blankenship et al. 2018a).
- SPoRT has contributed to the transition of Geostationary Lightning Mapper (GLM) observations from the new GOES-16 weather satellite to operational forecasters at the NOAA National Weather Service (NWS) and emergency management staff at NASA MSFC (Stano et al. 2018a). Notable outcomes include the development and contribution of official, NWS training material, development of the GLM stoplight safety product (Schultz et al. 2017, Stano et al. 2018a), and visualization of GLM flash, group, energy, and area data in NWS and NASA displays (Stano et al. 2018b).
- SPoRT has completed transition of Multispectral imagery from the Advanced Baseline Imager (ABI) from the new GOES-16 weather satellite to operational forecasters at the NOAA National Weather Service (NWS) SPoRT provided scientific guidance to NOAA NWS on the operational implementation of multispectral composites guiding technical implementation of SPoRT developed capabilities and improved, scientifically valid techniques to provide high-quality imagery to all forecasters across NOAA NWS (Fuell et al. 2016, Berndt et al. 2017, Berndt et al. 2018, McGrath et al. 2018).
- SPoRT has engaged with a series of new stakeholders within the drought monitoring community through the transition of the Evaporative Stress Index (ESI; Otkin et al. 2017; Yang et al. 2018, Lorenz et al. 2018; https://science.nasa.gov/earth-science/applied-sciences/making-space-for-

earth/seeing-stress-from-space). ESI is available operationally at the National Drought Mitigation Center, which is responsible for issuing the weekly U.S. Drought Monitor. A new global ESI product developed at NASA SPoRT and through a partnership with NASA-SERVIR, the experimental near-real-time global ESI products have made available to all SERVIR hubs through their cloud-based ClimateSERV platform.

Progress Assessment and Advanced Planning

PMM Science Team Meeting, October 16 – 29, 2017

The 2017 Precipitation Measurement Mission (PMM) Science Team meeting for TRMM and GPM (https://pmm.nasa.gov/meetings/all/2017-pmm-science-team-meeting) was held in San Diego, CA and consisted of three days 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 20, 2017. Working group meetings and the NASA-JAXA Joint PMM Science Team (JPST) board participated in a JPST meeting on October 16, 2017. Plans are underway for the 2018 meeting to be held in Phoenix, AZ on October 8-12, 2018. In addition, a new ROSES funded Science Team will be selected in FY19.

NASA Sounder Science Team Meeting, October 24 - 27, 2017

The NASA Sounder Science Team meeting (https://airs.jpl.nasa.gov/events/39) consisted of a variety of sessions on weather, climate, atmospheric composition, retrieval methods, applications and products, validation, and calibration, focused on NASA sounder science. The development and validation of unified retrieval algorithms for AIRS and CrIS was a special focus of the meeting and of the overall discussions.

CYGNSS Science Team Meeting, December 18, 2017

The CYGNSS science team convened at the NOAA Atlantic Oceanographic and Meteorological Laboratory or two days of meetings to review mission status, L1 and L2 algorithm development, early cal/val results in the aftermath of the 2017 Atlantic hurricane season, and on-going science investigations. The meeting topics and discussion are summarized in (NASA Earth Observer, Mar-Apr 2018).

AIRS Science Team Meeting, April 25-27, 2018

The Atmospheric Infrared Sounder (AIRS) Spring Science Team meeting (https://airs.jpl.nasa.gov/events/40) consisted of a variety of sessions on weather, climate, atmospheric composition, retrieval algorithms, validation, and calibration, focused on AIRS sounder science. In addition, this year there was a special session on the recent Earth Science Decadal Survey focused on how the sounder science community should respond and follow the Decadal Survey recommendations.

Working Group on Space-based Lidar Winds Meeting, February 7-8, 2018

More than 60 scientists and technologists representing NASA, NOAA, private industry, academia, and international organizations attended the meeting. The agenda included a number of important and very timely topics such as the Draft Earth Science and Applications from Space Decadal Survey, impending launch of the European Space Agency's Aeolus lidar wind mission, and current US activities associated with space-based wind lidar. Presentations on passive wind measurement techniques based on atmospheric motion vectors (AMVs) led off a session on potential synergisms between lidar and AMV observations for future missions. Action items identified for attention prior to the next meeting included response to the Decadal Survey, examination of potential use of US airborne wind lidar systems for Aeolus calibration and validation, and further investigation of combined lidar/AMV wind observation concepts.

16th JCSDA Technical Review & Science Workshop on Satellite Data Assimilation, May 30- June 1,2018
The annual JCSDA Technical Review Meeting and Science Workshop facilitates coordination between the partner agencies and research and development efforts supported by these organizations, and provides an in-depth assessment of the recent and upcoming development sponsored by the JCSDA.

CYGNSS Science Team Meeting, June 18-20, 2018
The CYGNSS science team meeting covers L1 and L2 algorithm development, continuing cal/val results, and on-going ocean and land science investigations.

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FY 2018 Annual Performance Indicator	FY15	FY16	FY17	FY18
ES-18-3: Demonstrate planned progress in improving the capability to predict weather and extreme weather events.	Green	Green	Green	Green

Annual Performance Indicator ES-18-6: 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. Sub-orbital 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.

High latitude ecosystem processes (Marine/Terrestrial)

High latitude regions continue to have some of the most rapidly changing ecosystems on Earth. New analyses have allowed better understanding of how key ecological properties are changing across space and time. For example, novel seascape classification approaches developed for the Western Antarctic Peninsula (WAP), based on a variety of biogeochemical variables, allow researchers to identify geographic regions and time periods with different distributions of phytoplankton chlorophyll *a* and nutrients, which can impact higher trophic levels in the WAP marine ecosystem (Bowman et al, 2018). Additionally, modeling of phytoplankton blooms near the Arctic suggest that changes in Arctic sea ice cover, and consequent freshwater export to the Labrador Sea, will impact the ocean mixed layer depth and, subsequently, phytoplankton, potentially reducing the primary producers' population during the wintertime (Balaguru et al., 2018).

Tundra ecosystems are becoming more productive (greening) (Epstein et al., 2017; Romanovsky et al., 2017) and shrubbier, which affects wildlife and climate feedbacks. However, the amount and distribution of plant biomass remains highly uncertain. Berner et al. (2017) mapped plant and shrub aboveground biomass (AGB) across northern Alaska at 30 m resolution using >2,000 Landsat scenes and field biomass harvests. Changes in plant AGB, shrub AGB, and shrub dominance were examined along regional gradients in air temperature. Landsat peak summer NDVI is a robust predictor of plant AGB in tundra ecosystems. Plant AGB and shrub dominance both notably increased with higher summer air temperatures. Therefore, continued warming will likely increase plant AGB and shrub dominance in tundra ecosystems across northern Alaska. These ecological responses to warming can be monitored both regionally and across the broader tundra biome using Landsat combined with field measurements.

Parts of boreal North America are vulnerable to increasing tree mortality from drought, pests, and pathogens. Early warning signals of mortality can be detected in growth trends decades before death, but had not yet been assessed with remote sensing. Rogers et al. (2018) assessed the potential for long-term NDVI from several satellite sensors (Landsat, MODIS, and AVHRR) to detect early warning signals of tree mortality in forest inventories across Alaska and central-western Canada. Results indicated potential to use satellite NDVI for early warning signals of tree mortality 2-24 years before death. Relationships are broadly consistent across inventories, species, and sensors, although coarse imagery in the heterogeneous aspen parkland is of limited utility. Such a tool could identify vulnerable landscapes and inform preventative land management.

Treat et al., (2018) reported that wetlands are the single largest natural source of atmospheric methane (CH_4), a greenhouse gas, and occur extensively in the northern hemisphere. Large discrepancies remain between "bottom-up" and "top-down" estimates of northern CH_4 emissions. Nongrowing season and annual CH_4 flux measurements from temperate, boreal, and tundra wetlands and uplands were synthesized. Median nongrowing season wetland in marshes were dependent on moisture, vegetation, and permafrost. Annual wetland emissions ranged from 0.9 g m^{-2} $year^{-1}$ in tundra bogs to 78 g m^{-2} $year^{-1}$ in temperate marshes. Uplands varied from CH_4 sinks to CH_4 sources with a median annual flux of 0.0 ± 0.2 g m^{-2} $year^{-1}$. The measured fraction of annual CH_4 emissions during the nongrowing season (observed: 13% to 47%) was significantly larger than that was predicted by two process-based model ensembles, especially between 40° and 60°N (modeled: 4% to 17%). Constraining the model ensembles with the measured nongrowing fraction increased total nongrowing season and annual CH_4 emissions. Using this constraint, the modeled nongrowing season wetland CH_4 flux from >40° north was 6.1 ± 1.5 Tg/year, three times greater than the nongrowing season emissions of the unconstrained model ensemble. The annual wetland CH_4 flux was 37 ± 7 Tg/year from the data-constrained model ensemble, 25% larger than the unconstrained ensemble. Considering nongrowing season processes is critical for accurately estimating CH_4 emissions from high-latitude ecosystems, and necessary for constraining the role of wetland emissions in a warming climate.

Environmental changes have had dramatic effects on the abundance, range and movement of animal populations. For instance, Laidre et al (2017) found that polar bear populations in Greenland have significantly contracted their range areas between the 1990s and 2000s in response to remotely sensed sea ice cover. Bears remained closer to land in winter and spring moving away from narrow ice straits and decreasing movement among previously connected populations. In addition, snow properties such as depth and density can strongly affect wildlife movements and survival. These properties can be modeled using fractional snow covered area and albedo from MODSCAG combined with weather data, but linking to wildlife requires new ground measurements. Prugh et al (2018) recorded sink depths of 44 Dall sheep snow tracks in Wrangell St-Elias National Park, Alaska, and measured the density of the associated snowpack. Snow with density ≥ 329 (±18 SE) kg/m^3 consistently supported the weight of adult Dall sheep (sink depth < 4 cm), allowing for easy travel. This study is a first step in linking snow properties to the energetics of animal travel. Furthermore, van de Kerk et al (2018) found that remotely-sensed late spring snow cover negatively affected Dall lambs, and this effect amplified with latitude. These results highlight the importance of spring snow phenology on the dynamics of iconic northern wildlife and suggest that northern Dall sheep populations may be more sensitive to changing snow conditions than their southern counterparts. Given these influences, we have supported the development of species monitoring tools that track species distribution and abundance using a combination of in-situ and satellite data. For instance, the Mapping Application for Penguin Populations and Projected Dynamics (MAPPPD) project uses Landsat measurements to forecast global Adélie penguin population and inform conservation decision making in the Southern Ocean (Che-Castaldo et al 2018). This toolset has been used to identify previously unknown populations of Adélie penguins, determined that the Danger Islands off the northern tip of the Antarctic Peninsula serves as a seabird hotspot (Borowicz et al 2018), and has been applied to discovery of other Antarctic bird populations (Schrimpf et al 2018, Schwaller et al 2018).

Permafrost on the biologically rich Yukon-Kuskokwim Delta (YKD) is at high risk of thawing, and high-resolution maps of current permafrost extent are crucial for monitoring and characterizing impacts to ecosystem structure and function. What are the best methods to map YKD permafrost, and are these methods effective in other environments? Whitley et al. (2018) parameterized and validated models mapping permafrost using LiDAR and optical satellite imagery. Using LiDAR data with a simple elevation threshold yielded 95% accuracy in mapping permafrost extent on the central YKD. This approach worked better than LiDAR integrated with optical data, and was much easier to model. High-resolution LiDAR maps permafrost extremely well in flat landscapes where ground-ice is the chief mechanism producing topography. Such landscapes are common on floodplains and many other lowland landscapes in “warm” permafrost regions.

Pastick et al (2018) used satellite remote sensing and climate reanalysis data to fingerprint the sensitivity of Alaska’s ecosystems to changing environmental conditions and disturbances. Approximately 13% (~174,000 ± 8700 km^2) of Alaska has experienced change over the last 32 years, with the majority of change processes occurring in coastal, riverine, and boreal ecozones (e.g. wildfire, glacial retreat, shrub expansion). Increasing air temperatures have generally promoted vegetation growth, while increases in evaporation have resulted in drought stress predisposing vegetation to mortality from other stressors. The reconstruction of landscape change fills a critical gap in the understanding of the historical and potential future trajectories of change in Alaska, with direct relevance to other northern high latitude regions.

Tropical Ecosystem Dynamics

Research focused on understanding processes controlling carbon cycling in tropical forests. Baccini et al. (2017) used MODIS data from 2003 to 2014 to track vegetation changes associated with disturbance and forest recovery in live forests across tropical America, Africa, and Asia (between 23.45 ^{o}N and 23.45 ^{o}S excluding Australia), including losses from land-use change and degradation/disburbance as well as gains from growth. Tropical forests were a net source of 425 ± 90 Tg C/yr over this time period. This net release of carbon accounted for 861.7 ± 80.2 Tg C yr^{-1} in losses, and gains of 436.5 ± 31.0 Tg C yr^{-1}. Gains resulted from forest growth; losses from deforestation and from reductions in carbon density within standing forests (degradation/disturbance), with the latter accounting for 68.9% of overall losses.

Carlson et al. (2018) showed that sustainability certification of oil palm plantations in Indonesia result in reducing deforestation by 33% compared to non-certified plantations.

Liu et al. (2017) showed that compared to the 2011 El Nino period, on a global basis, tropical regions released 2.5 Gt more carbon during the 2015/2016 El Nino. This difference is largely driven by significant increases in fire activity during El Niño years compared to La Nina years. Additionally, 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. The 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 by ecosystem.

Over the course of six El Niño events, Chen et al. (2017) found that reductions in precipitation and terrestrial water storage increased fire emissions in pan-tropical forests by 133% during and following El Niño as compared with La Nina. Fires peaked in equatorial Asia early in the ENSO cycle when El Niño was strengthening (Aug-Oct), before moving to southeast Asia and northern South America (Jan-Apr), Central America (Mar-May) and the southern Amazon (Jul-Oct) during the following year. The predictable cascade of fire across different tropical continents described highlights an important time delay in the Earth system's response to precipitation redistribution. These observations help to explain why the growth rate of atmospheric CO2 increases during El Niño and may contribute to improved seasonal fire forecasts.

Use of solar induced fluorescence to analyze productivity

Sun et al. (2018) highlighted the scientific importance of the solar induced fluorescence data provided by OCO-2 by demonstrating that there is a linear relationship between SIF and tower-measured GPP, providing a better satellite-based metric than LAI for studying global and regional patterns of NPP.

Parazoo et al. (2018) used a model constrained by airborne and tower CO2 measurements and OCO-2 SIF measurements to examine the relationship between spring thaw date and the onset of GPP and net carbon uptake in tundra and boreal forests in Alaska. They found that while thaw occurred earlier in boreal forests, that the lag between thaw and the onset of GPP and net carbon uptake was longer in forests than in tundra.

Xiao et al. (2018) conducted the first global analysis of the relationship between OCO-2 SIF and tower GPP based on 64 flux sites across the globe encompassing eight major biomes. The generally consistent slope of the relationship among biomes suggests a nearly universal rather than biome-specific SIF-GPP relationship. OCO-2 SIF had a better performance for predicting GPP than MODIS vegetation indices and a light use efficiency model. The universal SIF-GPP relationship can lead to more accurate GPP estimates regionally or globally. Revealed the remarkable ability of finer-resolution SIF observations from OCO-2 and other new missions (e.g., TROPOMI, FLEX) for estimating photosynthesis globally.

Shiga et al. (2018) used a network of atmospheric CO2 observations over North America to explore the value of SIF for informing net ecosystem exchange (NEE) at regional scales. They found that SIF explained space-time NEE patterns at regional (~100 km2) scales better than a variety of other vegetation and climate indicators. They further showed that incorporating SIF into an atmospheric inversion led to a spatial redistribution of NEE estimates over North America, with more uptake attributed to agricultural regions and less to needleleaf forests.

Köhler et al. (submitted). First solar induced chlorophyll fluorescence (SIF) observations from TROPOMI near infrared band measurements. Unprecedented spatio-temporal resolution of global SIF maps. Inter-sensor comparison between TROPOMI and OCO-2 SIF data shows excellent agreement.

Urban Systems in Land Cover and Land Use Change

Despite the degradation of urban environment associated with the rapid urbanization, limited studies have examined the spatial patterns and driving factors of urban environmental quality (UEQ) in mountainous cities in China. Using a case study of Chongqing, Liu et al. (2017), reported on UEQ in mountainous with regard to the physical environment, built environment, and natural hazards, followed by an exploration of spatial pattern. It was found that the UEQ has been significantly affected by the factors of pollution and dense built environment. Pollution factor was highly correlated with industrial land ratio and land surface temperature, and dense built environment factor bore close relationship with road density, impervious fraction, and floor–area ratio. Through a cluster analysis, Chongqing was classified into five UEQ clusters and their spatial distribution was found as a combined polycentric and mosaic pattern. While mountains and hill ridges, riverside banks, small hills, and streams showed high UEQ indices, valley floors exhibited low UEQ values. Polycentric urban development adapting to mountainous landscapes was believed to contributing to the extremely low UEQ in urban center and subcenters. However, polycentricity, leading to appropriate spatial match of jobs/housing, also resulted in high UEQ in the peripheries.

Kingfield et al., (2017) examined the role of city size on thunderstorm occurrence and strength utilizing multi-radar climatology of Weather Service Radar of of maximum expected size of hail (MESH) and vertically integrated liquid (VIL) around four cities: Dallas–Fort Worth, Texas; Minneapolis–St. Paul, Minnesota; Oklahoma City, Oklahoma;

and Omaha, Nebraska. This research built upon previous studies that examine urban-weather phenomenon, and particularly remote sensing data from (e.g., MODIS, VIIRS, OMI, TM/ETM+, ASTER, and Orbview-3). A storm-tracking algorithm identified thunderstorm areas every minute and connected them together to form tracks. When examining all thunderstorm events, regions at variable ranges upwind of all four cities generally had higher areal mean values of reflectivity, MESH, and VIL relative to downwind areas. A subset of events, UF (urban favorable), corresponding to favorable conditions for urban modification was explored This urban favorable (UF). In the UF subset, the larger cities (Dallas–Fort Worth and Minneapolis–St. Paul) had a 24%–50% increase in the number of downwind thunderstorms, resulting in a higher areal mean reflectivity, MESH, and VIL in this region. The smaller cities (Oklahoma City and Omaha) did not show such a downwind enhancement in thunderstorm occurrence and strength for the radar variables examined. This pattern suggests that larger cities could increase thunderstorm occurrence and intensity downwind of the prevailing flow under unique environmental conditions.

Ecosystems and Human Health

Harmful Algal Blooms (HABs) and other unpredictable events, such as oil spills, heatwaves, and blooms of macroalgae impact aquatic ecosystems and have the potential to impact human health. Remote sensing techniques provide the possibility to estimate, monitor, and predict the potential impacts of these events on ocean ecosystems, human health, and even economics. Sustained observations on event-scale phenomena at different temporal and spatial scales are critical to understand and eventually manage the impacts of these events. For example, Sahay et al (2017) applied satellite informed abundance models to estimate monsoon driven changes in Arabian Sea phytoplankton biomass during a major *Noctiluca scintillans* bloom that has been attributed with lowering phytoplankton diversity. Hu et al. (2018) combined remote sensing imagery of different spatial and temporal resolution to map the surface oil volume during the DeepWater Horizon oil spill in the Gulf of Mexico that occurred between April – July 2010. The team was able to derive maps of surface oil volume and relative oil thickness, information that is critical to assess the impact of the spill to the surrounding ecosystems; the maps of surface oil volume and relative thickness will be very useful for oil spill response and mitigation by providing maps of hydrocarbon impacted areas on which managers can concentrate relief efforts. Approaches employed in the aforementioned Deepwater Horizon management efforts via the remotely sensed data are being used in estimating the extent of oil spills in other regions, such as the East China Sea (Sun et al., 2018). As for other aquatic events, marine heatwaves are anomalous events of broad-scale warming within a region. One of the most notable was the so-called “Blob” in the northeast Pacific between 2014–2016. Such widespread heating events impact the local aquatic biology and disrupt local ecosystem function. During the “Blob,” dramatic changes to phytoplankton and zooplankton abundances and community composition were noted, which impacted higher trophic levels (fisheries, marine mammals, etc.). The area of widespread warming also affected the occurrence of different types of ocean fronts, which are areas that have been associated with increased primary production and which play an important role in the functioning of marine ecosystems (Kahru et al., 2018). During the anomalously warm 2014–2016 period, the frequency of fronts decreased, and was associated with reduced chlorophyll and warmer sea surface temperatures.

Atmosphere-Ocean-Land exchanges and feedbacks (integrated ecosystem response to environmental change)

The Earth System is changing at unforeseen rates. Understanding the impact of these environmental and climate changes on terrestrial and aquatic ecosystems is fundamental to ensure sustainability and resilience of communities and organisms and support the US economy and recreation. Several areas of the ocean are warming rapidly, such as the U.S. Northeast Continental Shelf, with changes in water temperatures potentially impacting marine ecosystems. By combining satellite and in situ data, it is possible to assess the impact of environmental changes to waters at the surface and near the sea floor, thus bracketing regions in the ocean that sustain important ecosystem services. Kavanaugh et al. (2017) showed that different areas within a larger region warm at different rates, and such regional changes are driven by different forcings even within the same shelf area; these results highlight the need to better understand how changes in the ocean may affect seasonally specific ecological processes and species, such as the American Lobster (Rheuban et al. 2017), on which humans depend for food and economics. The ability to discern seasonal and interannual variations in oceanic processes, and their impact on ecosystem services, is impossible without sustained, long-term ocean observations. Analyzing 30 years of in situ data at the Hawaii Ocean Time Series (HOT), together with satellite and modeled observations, Kavanaugh et al (2018) were able to identify secular trends in the North Pacific subtropical gyre, which induces ecosystem changes at the HOT Station, including changes in phytoplankton standing stocks and Net Primary Production (NPP), primarily in the deeper euphotic zone. Wetlands are also areas subject to a large amount of environmental and climate change over varying temporal periods; they are regions of extensive carbon burial over long periods, which is important for understanding the role of land/water interfaces in the global carbon cycle and the potential for sequestration of atmospheric carbon dioxide. However, because of their dynamic nature, carbon budgets are difficult to obtain, but very important for understanding issues facing coastal waters. Najjar et al. (2018) constructed the carbon budget for coastal waters of eastern North America and found that there were important transfers of carbon among wetlands, estuaries and the ocean; in particular, tidal wetlands and estuaries were found to be important to the carbon budget, despite making up only 2.4 and 8.9% of the study domain area, respectively.

Satellite approaches for estimation of the partial pressure of CO_2 (pCO_2) and air-sea flux of CO_2 in coastal regions offer the potential to reduce uncertainties in coastal carbon budgets and improve understanding of spatial and temporal patterns and the factors influencing them. Lohrenz et al. (2018) estimated the partial pressure of CO_2 (pCO_2) and air-sea flux of CO_2 in coastal regions of the Gulf of Mexico, using a combination of satellite-derived products and ship-based observations. They found that the region is mostly a sink of carbon, and were able to distinguish spatial and seasonal patterns associated with discharge from the Mississippi and Atchafalaya Rivers, as well as Gulf circulation. This research represents a significant advance in the understanding of

CO_2 fluxes in coastal zones, which are complex and poorly constrained; the approach utilized also has the potential to be applicable in other coastal regions.

Remote Sensing Advances in Marine and Terrestrial Ecosystems

Satellite ocean color data have provided critical information on biology, ecology and the carbon cycle for over four decades. Chase et al (2017) determined that several phytoplankton accessory pigments can be predicted using hyperspectral data, providing a crucial component in efforts to estimate phytoplankton groups from optical and ultimately satellite data. Schweiger et al (2018) demonstrated that dissimilarity of species' leaf spectra increases with functional dissimilarity and evolutionary divergence time. These findings are being used to remotely categorize the trait variation within and across species (even in the absence of taxonomic, functional, phylogenetic, or abundance information) that opens doors for ecosystem function and service monitoring. New advances in active sensor applications, such as lidar, to the ocean offer the potential to expand current approaches and fill critical information gaps. Hostetler et al. (2018) described the recent breakthroughs, including the ability of LiDARs to resolve water column vertical structure, which enables characterization of phytoplankton and suspended particulate distributions within the upper light field, leading to improved estimates of net primary production and carbon stocks. LiDARs could lead to a three-dimensional reconstruction of global ocean ecosystems and (carbon) particles while penetrating the waters up to three optical depths. Additionally, active sensors, such as lidar, provide their own illumination. Their measurements are not impacted by changes in solar illumination due to cloud cover (if the lidar is not fully blocked by cloud) or solar viewing geometry (a limitation for passive radiometers), and thus provide uninterrupted data in areas that are prone to significant cloud cover. Application of these tools is not limited to the marine realm. Schaffer-Smith et. al., (2018) demonstrated the utility of LiDAR, high-resolution satellite imagery, and field observations for monitoring hydrologic regimes and water depth distribution in wetland ecosystems. Using these data, the research team was able to map suitable shallow water habitat for migratory shorebirds in the Sacramento National Wildlife Refuge Complex. Effort is being put towards designing new sensors that would provide improved information about the carbon cycle; for example, Crowell et al. (2018) performed simulation studies where they demonstrated that new active missions can detect permafrost thaw and fossil fuel emissions shifts at annual and seasonal time scales, thus better constraining and complementing the current information being provided by OCO-2.

The vast extent and inaccessibility of boreal forest ecosystems are barriers to routine monitoring of forest structure and composition. Alonzo et al. (2018) bridge the scale gap between intensive but sparse plot measurements and extensive remote sensing studies by collecting forest inventory variables at the plot scale using an unmanned aerial vehicle (UAV) and a structure from motion (SfM) approach. They acquired overlapping imagery and generated dense, 3D, RGB (red, green, blue) point clouds. They used these data to model forest type at the individual crown scale as well as subplot-scale tree density (TD), basal area (BA), and aboveground biomass (AGB).They achieved 85% cross-validation accuracy for five species at the crown level. Precise estimation of TD required either segment counts or species information to differentiate black spruce from mixed white spruce plots. These results convey the potential utility of SfM data for forest type discrimination in FIA.

Terrestrial Disturbances (including drought)

Sulla-Menashe et al. (2018) analyzed Landsat data to show that disturbance explained most boreal greening and browning trends. In undisturbed forests, impacts were mostly restricted to ecotones. In eastern Canada, undisturbed forests show widespread greening in response to warming. In western Canada, undisturbed forests show modest browning in response to warming and periodic drought. Moderate spatial resolution time series of well-calibrated Landsat observations provide the basis for refined understanding regarding the nature and magnitude of changes in boreal forest ecosystem and productivity over the last three decades.

Melaas et al. (2018) conducted the first continental-scale analysis of multi-decadal changes in the timing of spring onset across North American temperate and boreal forests based on Landsat imagery. Leaf emergence in Eastern Temperate Forests has consistently trended earlier, with a median change of about 1 week over the 30 year study period. Changes in leaf emergence dates in boreal forests were more variable, with some sites showing trends toward later dates. Interannual variability in leaf emergence dates was strongly sensitive to springtime accumulated growing degree days across all sites, and geographic patterns of changes in onset dates were strongly correlated with changes in regional springtime temperatures. These results provide a refined characterization of recent changes in springtime forest phenology and improve understanding regarding the sensitivity of North American forests to climate change.

Forest degradation is widespread across the Amazon, yet degradation emissions are excluded from carbon monitoring systems like REDD+ due to data gaps on forest recovery from logging and fire. Rappaporte et al. (2018) analyzed forest inventory data, airborne lidar, and a 32-year Landsat time series to characterize forest carbon stocks and 3D forest structure 1-15 years following specific degradation pathways. Carbon stocks were lower in burned forests than logged forests, and repeated burning resulted in a non-linear decline in carbon stocks and habitat heterogeneity. Neither logged nor burned forests recovered their original carbon stocks within 15 years of recovery. This study provides the first comprehensive set of emissions factors needed to include logging and fire in estimates of carbon emissions from Amazon forests for REDD+, reduce uncertainty in the global carbon budget, and improve climate and land use projections.

Amazon droughts, including the 2015–2016 El Niño, may reduce forest net primary productivity and increase canopy tree mortality, thereby altering both the short- and the long-term net forest carbon balance. Given the broad extent of drought impacts, inventory plots or eddy flux towers may not capture regional variability in forest response to drought. Leitold et al. (2018) used multi-temporal airborne lidar data and field measurements of coarse woody debris to estimate patterns of canopy turnover and associated carbon losses in intact and fragmented forests in the central Brazilian Amazon between 2013–2014 and 2014–2016. El Niño conditions accelerated canopy turnover in central Amazon forests, increasing coarse woody debris production by 62% to 1.22 Mg C ha-1 yr-1 in drought years.

Schwalm et al. (2017) examined the relationship between drought and GPP on a global basis, and found that drought impacts on GPP has increased in frequency during the 20th century, and that the two regions (boreal and tropics) experiencing the greatest climate change also take the longest to recover from the impacts of drought.

Shi et al. (2017) used the Community Land Model version 4.5 (CLM4.5) and radar backscatter observations from SeaWinds Scatterometer on board QuikSCAT (QSCAT) satellite to investigate the relative role of biotic (plant structure damage) versus environmental factors (e.g., water stress) in controlling the forest canopy disturbance and recovery processes after the 2005 Amazonian drought. The results showed (1) the strength of scatterometer backscatter measurements in capturing canopy damage over tropical forests and for validating C cycle models and (2) biotic factors play the dominant role in regulating the drought induced disturbance and persistent canopy changes.

In the US, lethal predator control programs have been implemented to mitigate declines in threatened and endangered species and to benefit economically valuable prey species. These management actions can be conducted on the basis of assumed impacts of predation rather than a mechanistic understanding of predator-prey interactions. To build a more informed system, Mahoney et al (2018) developed a modelling approach to determine the overlap between removal of animal predators and protecting habitat for pregnant deer in south-central Utah. These models incorporate remotely sensed spatial covariates to quantify species-specific resource selection or predator vulnerability to aerial removal.

Field Campaigns

NASA supports several Earth Venture Suborbital and other combined airborne/field campaigns that contributed to the assessment of Earth's marine biogeochemistry, ocean biology, 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 in areas such as Hawaii, the Great Barrier Reef, and the South Pacific. The CORAL project is in its synthesis phase , and over the past year the team has been processing the airborne PRISM data and finalizing their field data analysis. A final science team meeting is planned for August 2018.

Complementing the CORAL project, NASA conducted another round of flights in Hawaii of the high-altitude ER-2 aircraft in early 2018. The ER-2 carried the Airborne Visible/Infrared Imaging Spectrometer-Classic (AVIRIS-C) sensor and the MODIS/ASTER (MASTER) airborne simulator as in early 2017 but also included the PRISM and Hyperspectral Thermal Emission Spectrometer (HyTES) instruments. The targets for this first-of-its-kind suite of airborne imaging spectrometers—ranging from the ultraviolet through the thermal infrared on the electromagnetic spectrum—were the coral reefs and active volcanoes of the Aloha State. In addition to Hawaii, NASA continues to acquire summer acquisitions with the AVIRIS-C and MASTER instruments on the ER-2 aircraft over five very-large area boxes and a long transect within the state of California. The data from summer 2018 represent the sixth consecutive year of NASA's capturing visible to shortwave infrared imaging spectroscopy and multispectral thermal infrared data over the same large expanses of California, chronicling a major drought event.

NASA's Global Ecosystem Dynamic Investigation (GEDI) mission has been designed to measure forest structure using lidar waveforms to sample the earth's vegetation while in orbit aboard the International Space Station. Silva et al. (2018) used airborne large-footprint (LF) lidar measurements to simulate GEDI observations from which they retrieved ground elevation, vegetation height, and aboveground biomass (AGB). GEDI-like product accuracy was then assessed by comparing them to similar products derived from airborne small-footprint (SF) lidar measurements. The study focused on tropical forests and used data collected during the NASA and European Space Agency (ESA) AfriSAR ground and airborne campaigns in the Lope National Park in Central Gabon. The comparison of the two sensors shows that LF lidar waveforms and simulated waveforms from SF lidar are equivalent in their ability to estimate ground elevation (RMSE = 0.5 m, bias = 0.29 m) and maximum forest height (RMSE = 2.99 m, bias = 0.24 m) over the study area. The difference in the AGB estimated from both lidar instruments at the 1-ha spatial scale was small over the entire study area (RMSE = 6.34 $Mg \cdot ha^{-1}$, bias = 11.27 $Mg \cdot ha^{-1}$) and the bias was attributed to the impact of ground slopes greater than 10–20° on the LF lidar measurements of forest height. These results support the ability of GEDI LF lidar to measure the complex structure of humid tropical forests and provide AGB estimates comparable to SF-derived ones.

The North Atlantic Aerosols and Marine Ecosystems Study (NAAMES; http://naames.larc.nasa.gov) combines atmospheric and oceanographic airborne and ship observations with continuous satellite sensor records to *define environmental and ecological controls on plankton communities and to improve predictions of their structure and function in a warmer future ocean*. NAAMES also seeks to connect atmospheric and ocean science by *defining linkages between ocean ecosystem properties and biogenic aerosols to improve predictions of marine aerosol-cloud-climate interactions with a warmer future ocean (Sanchez et al, 2018).* The fourth and last NAAMES cruise in the North Atlantic was completed in April 2018 with a four-week duration. The team held their science team meeting in June 2018 to begin synthesizing the range of data collected over the duration of the project. The project has published fifteen peer-review publications thus far, with five in the journal *Nature*.

The EXport Processes in the Ocean from RemoTe Sensing (EXPORTS; https://cce.nasa.gov/ocean_biology_biogeochemistry/exports/index.html) project has a major field campaign 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; the science team held three science and planning meetings over 2017-2018, and will begin the first scientific campaign in August-September 2018. This 2018 campaign will take place in the Northeast Pacific and will employ two research vessels as well as a wide array of autonomous platforms to complement the shipboard data. 58 scientists are anticipated to participate in this first field campaign.

During the active season of 2017, several states were hit by hurricanes. NASA, through the Rapid Response and Novel Research in Earth Science (RRNES) program, supported research to understand the impact of those severe storms on land and coastal ecosystems, and water quality. For example, Joshi and D'Sa (2018) utilized a tuned multiband Quasi-Analytical Algorithm (QAA-5 V) optimized to estimate IOPs in optically shallow and near-shore waters for VIIRS to assess suspended particulate matter (SPM) in Galveston Bay following Hurricane Harvey, and its impact on the coastal ocean. Very high SPM concentrations in the Bay persisted over several days, with wind forcing influencing its distribution into the shelf waters of the northern Gulf of Mexico.

Workshops and Team Meetings

The South/Southeast Asia Regional Initiative (SARI) is an ongoing initiative to tackle environmental problems in South and Southeast Asia. The NASA LCLUC Program has been supporting SARI activities during the last three years, with some of the projects funded through its recent solicitations. SARI workshops promote collaboration and interactions with the regional scientists – usually 2-3 workshops a year – in coordination with SERVIR, GFOI and SilvaCarbon. Working meetings are the primary venues at which regional scientists, representing different countries, are brought together to discuss complex regional change issues and methods to study them. As the leading civil space agency, NASA invest in developing regional capacity to use remote sensing observations, needed for validating and promoting NASA data products. This is accomplished by having training at each and every international regional SARI workshop. SARI leadership assures that NASA data products are understood and communicated appropriately.

The fourth PACE Science Team (ST) meeting was held during mid-January 2018 at the Harbor Beach Oceanographic Institute in Florida, USA. The meeting consisted of a virtual, self-paced segment in which science team members prepared and viewed narrated versions of their project presentations in preparation for the meeting, followed by an in-person meeting. Science Team members formed break-out groups to discuss the status of major project areas, focusing on identifying research, modeling, observational, and technology challenges, needs, and input regarding the retrieval of inherent optical properties (IOP) and atmospheric corrections (AC) for the PACE mission. The IOP team has published a synthesis peer-reviewed paper with their findings (Werdell et al, 2018), and the AC team continues to work towards a synthesis of input in a formal NASA Technical Memorandum due to NASA in summer 2018. NASA also reviewed the final results of three investments in the vicarious calibration of ocean color instrumentation in support of PACE ocean measurements.

The ECOSTRESS Science Team met on June 29 and 30 to plan for the utilization of ECOSTRESS' multispectral thermal infrared imagery. They were able to view the successful launch of the instrument to the International Space Station and. The focus of the mission is evapotranspiration, plant water use efficiency, and evaporative stress.

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FY 2018 Annual Performance Indicator	FY 15	FY16	FY17	FY18
ES-18-6: Demonstrate planned progress in detecting and predicting changes in Earth's ecological and chemical cycles, including land cover, biodiversity, and the global carbon cycle.	Green	Green	Green	Green

Annual Performance Indicator ES-18-7: 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.

Research funded by NASA's Water and Energy cycle focus area (WEC) seeks to improve our fundamental understanding of the water and energy cycle by developing tools and techniques that expand our ability to detect, measure, track, model, and forecast global water storage and dynamics, to quantify how energy is transferred from the tropics to higher latitudes, and to expand our ability to assess water quality. The WEC community uses satellite and airborne remote sensing observations in conjunction with *in situ* field measurements to advance our scientific understanding of the natural and anthropogenic processes influencing water distribution and to predict how changing climatic factors may influence water availability thereby improving societies ability to manage water resources. 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, hydrologic remote sensing field experiments, and identifies new capabilities that have the potential to support decision makers.

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 and quantification of each water cycle element to determine the global water budget, and the ability to measure and track the energy exchange when water changes phases. The WEC research portfolio is an ongoing balance of supporting research that can be advanced with the current constellation of airborne and satellite sensors, preparing for new missions that are under construction (i.e. SWOT, NISAR, GEDI, ICESat2), and identifying new and innovative techniques/technology that will allow us to ask the next generation of scientific questions that were not possible a few years ago, all within the budget profile. Below are highlights of WEC Focus Area funded research accomplishments that have matured in FY2018 and represent research that has been funded over the past several ROSES cycles.

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, GPM, MODIS) and new research supporting missions that are either recently launched (GRACE-FO) or are in development (i.e. SWOT and 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 reanalysis. 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. It begins with three cross cutting publications by Rodell *et al.*, Huntington *et al.*, and Allen *et al.*

Accurate accounting of changes in freshwater availability is essential for predicting regional food supplies, human and ecosystem health, and energy generation. Groundwater is particularly difficult to monitor and manage because aquifers are vast and unseen, yet groundwater meets the domestic needs of roughly half of the world's population and boosts food supply by providing for 38% of global consumptive irrigation water demand. Rodell *et al*. (2018, *Nature*) analyzed 14 years of GRACE data collected between 2002-2016 by quantifying 34 trends in terrestrial water storage (TWS), categorized their drivers as natural interannual variability, unsustainable groundwater consumption, or climate change, and found that freshwater availability is changing worldwide. By far the largest TWS trends were found to occur in Antarctica, Greenland, the gulf coast of Alaska, and the Canadian archipelago, where the warming climate continues to drive rapid ice sheet and glacier ablation. Excluding those four ice-covered regions, freshwater was found to be accumulating in far northern North America and Eurasia and in the wet tropics, while the greatest non-frozen freshwater losses have occurred at mid-latitudes. Their investigation found that several of these trends had been lacking thorough investigation and attribution, including massive changes in northwestern China and the Okavango delta. Others were found to be consistent with climate model predictions. Their observation-based assessment of how the world's water landscape is responding to human impacts and climate variations provides a blueprint for evaluating and predicting emerging threats to water and food security.

Climate change is intensifying or ''speeding up" the global water cycle by increasing rates of ocean evaporation, terrestrial evapotranspiration, and precipitation, where intensification is defined as an increase in the flux of water between existing ocean, atmosphere, terrestrial, freshwater, and cryospheric pools. Huntington *et al.* (2018, *J. of Hydrology*) developed a quantitative framework for characterizing the intensity of the water cycle over land by using a spatially distributed water-balance model of the conterminous United States. Their approach for assessing water cycle intensity (WCI) was from a landscape perspective where they assessed runoff as a function of precipitation, actual evapotranspiration, and soil moisture storage dynamics over a spatially explicit landscape unit of interest, averaged over a specified time period of interest. They found that WCI increased over most of the lower United States between the 1945 to 1974 and 1985 to 2014 periods was driven primarily by increases in precipitation. In portions of the western and southeastern US, storage-adjusted runoff decreased because of there were drop in both actual runoff and soil moisture storage. Furthermore, they suggested that analysis of WCI and storage-adjusted runoff at temporal scales ranging from sub-daily to multi-decadal could improve the understanding of the wide spectrum of hydrologic responses that have been attributed to water cycle intensification.

The turbulent surfaces of rivers and streams are natural hotspots of biogeochemical exchange with the atmosphere. At the global scale, the total river-atmosphere flux of trace gasses such as CO_2 depends on the proportion of Earth's surface that is covered by the fluvial network, yet the total surface area of rivers and streams is poorly constrained. Allen and Pavelsky (2018: *Science*) used a global database of planform river hydromorphology developed for SWOT and a statistical approach to show that global river and stream surface area at mean annual discharge is 773,000 ± 79,000 km^2 of Earth's non-glaciated land surface, an area 44 ± 15% larger than previous spatial estimates. They also found that rivers and streams likely play a greater role in controlling land-atmosphere fluxes than currently represented in global carbon budgets. The surface area of rivers and streams in the Arctic is higher than previously thought, while in many developed areas it is lower. The key finding from this study was that the flux of CO_2 from rivers and streams to the atmosphere is likely substantially higher than previously thought.

Snow

Snow remains one of the significant challenges to remote sensing of the water cycle. Unlike with 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. Therefore, WEC continues to invest in a variety of research and technical approaches to better characterize snow. The Focus Area 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. This GPRA cycle produced a number of publications advancing our understanding and capabilities in snow science including a continental scale investigation assessing SWE and developing new estimations of snow accumulation from regional models, a study on dust radiative contribution to snowmelt runoff, a new satellite imagery downscaling approach, and the development of new remote sensing radar technology for snowpack assessment.

Mountain ranges are often described as natural water towers, storing winter snowfall and releasing water in warm months to provide crucial resources for ecosystems, agriculture, and other human enterprises. Despite the importance of snow, snow storage estimates are highly uncertain, particularly in areas with complex topography and when assessed from one mountain range to another, let alone on a continental/global scale where no reliable mountain snow climatology exists. Wrzesien *et al.* (2018: *Geophysical Research Letters*) estimated mountain SWE for North America from regional climate model simulations and found that the climatological peak SWE in North America mountains is 1,006 km^3, 2.94 times larger than previous estimates from reanalysis. By combining this mountain SWE value with the best available global product in non-mountain areas, they estimated peak North America SWE of 1,684 km^3, 55% greater than previous estimates. They compared modeled SWE with ground observations from snow pillows, daily SWE measurements at 757 *in situ* points in total. They also compared their estimate of total North American SWE to the Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage (TWS) anomaly observations for 2003 through 2010 to understand the role of SWE in the continental water storage budget. Though mountains comprise 24% of the continent's land area, the study estimated that they contain ~60% of North American SWE. This investigation will help benchmark future continental- and global-scale water and energy budget studies.

Reliable maps of snow-covered areas at scales of meters to tens of meters, with daily temporal resolution, are essential to understanding snow heterogeneity, melt runoff, energy exchange, and ecological processes. Cristea *et al.* (2017: *Water Resource Research*) developed a parsimonious downscaling routine that can be applied to fractional snow-covered area products from satellite platforms such as the MODIS that provide daily 500 m data, to derive higher-resolution snow presence/absence grids. They accomplished this by creating a framework based on airborne-derived high-resolution (3 m) snow data to test their terrain-based downscaling technique that uses coarse spatial resolution fractional snow-covered data to derive higher-resolution binary (presence/absence) snow maps that include the effects from both accumulation and ablation processes. Their downscaling approach will improve our ability to better characterize snow surface extent from lower resolution/higher revisit satellite imagery.

Worldwide, snowmelt and glaciers provide agricultural and urban water resources for about two billion people. Thus, the timing and magnitude of snowmelt rates control the timing and rates of soil moisture and river discharge, which, in turn, influence water availability, flood potential, hydroelectric generation, and water quality. Painter *et al.* (2018: *Geophysical Research Letters*) addressed the question, do air temperatures or absorbed solar radiation explain the year-to-year variability of the rate of snowmelt and therefore the shape of the way the streamflow rises in the melt season? Their analysis showed that absorbed solar radiation, which varies with the amount of wind-blown dust deposited into the snowpack, causes the streams to rise more quickly in years with more dust, whereas the rate at which the streams rise does not depend on air temperature. These observations suggest that hydroclimatic modeling must be improved to account for aerosol forcings of the water cycle. Anthropogenic climate change will likely reduce total snow accumulations and cause snowmelt runoff to occur earlier. However, dust radiative forcing of snowmelt is likely consuming important adaptive capacity that would allow human and natural systems to be more resilient to changing hydroclimatic conditions.

Three major snow properties influence the water content of a frozen snowpack: snow cover, snow depth, and snow density. Currently, each parameter is measured independently to produce a robust SWE estimate. Kim *et al.* (2018: *Microwave Theory and Techniques IEEE Transactions*) outlined the development of an innovative Ku-band CMOS frequency-modulated continuous-wave (FMCW) radar to improve depth measurements of dry snow toward producing more precise SWE estimates. In their approach, a radar is flown on a small unmanned aerial vehicle (UAV) at low altitudes in the range of 100 m to overcome the aperture limited spatial resolution of space-borne microwave snow sensing. The implemented radar system was deployed at Mammoth Mountain to perform real snow measurements and shows a good agreement with in situ snow depth measuring equipment.

Surface water

The focus area has made investments to improve our ability to resolve surface water and measure river discharge, including preparing for the upcoming SWOT Mission. Both are important topics 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. Furthermore, as we prepare for the SWOT and NISAR missions, and data from the recently launched GRACE-FO missions become available, technology and algorithm development are beginning to support new scientific advancements with increasing contributions in future GPRA cycles. The SWOT Science Team produced a number of articles this past year that either focused on advancing our understanding of fluvial processes or providing valuable insights into specifically elements supporting the development of SWOT. The Allen and Pavelsky (2018: *Science*) article discussed above in detail is an example of new high-impact science from algorithms and databases developed for SWOT. Below is a summary of several SWOT related publications along with a study assessing the impact of land cover change on river discharge utilizing GRACE measurements.

The SWOT Science Team had a very productive year with a number of publications supporting the mission development. Gleason *et al.* (2017: *EOS*) introduced the global AGU community to the surface water component of the SWOT mission and provided a mission overview along with challenges faced by the Science Team in an article titled, "Tracking River Flows from Space". Frasson *et al.* (2017: *Water Resources Research*) evaluated three different automated river segmentation strategies for defining optimum reaches for discharge estimation and found that in general, height, width, and slope errors decrease with increasing reach length and found that reach definition methods that preserve the hydraulic properties of the river network may lead to better discharge estimates. Oubanas *et al.* (2018: *Journal of Hydrology*) investigated river discharge estimation from synthetic SWOT observations for a 50 km-long reach of the Garonne River in 2010 that included multiple flood events where the synthetic SWOT data had high-uncertainties in the model inputs (river bathymetry and bed roughness) compared with in situ field measurements. They found that the assimilation of the SWOT data results into an accurate estimation of the discharge at observation times, and a local improvement in the bed level and bed roughness coefficient. Domeneghetti *et al.* (2018: *Journal of Hydrology*) developed a SWOT data simulator that ingests collected river surface parameters along a 140 km segment of the Po River in Norther Italy to evaluate SWOT performance under different hydraulic conditions and assess possible effects of river embankments, river width, river topography and distance from the satellite ground track. Collectively these publications are not only supporting the development of SWOT, but they are providing new insights into surface water processes.

Earth-orbiting satellites provide valuable observations of upstream river conditions worldwide that can be used in real-time applications like early flood warning systems and reservoir operations, provided they are made available to users with sufficient lead time. Allen *et al.* (2018: *Geophysical Research Letters*) apply a kinematic wave model to a global hydrography data set to approximation of flow wave travel time to assess the utility of existing and future low-latency/near-real-time satellite products, with an emphasis on the forthcoming SWOT satellite mission. They found that global flow waves traveling at their maximum speed take a median travel time of 6, 4, and 3 days to reach their basin terminus, the next downstream city, and the next downstream dam, respectively. Their findings suggest that ≤2-day data latency for a low-latency SWOT product is potentially useful for real-time river applications, including aiding early flood warning systems in cities and reservoir operation management at dams. Analyses, such as this by Allen *et al.* are being used by the SWOT Science Team and are influencing the mission: SWOT product data latency was just changed (June 2018) from about 30 days to approximately 3 days from data collection to the release of the products.

Charactering and isolating natural, climatic, and anthropogenic parameters that influence long-term changes in surface water can be daunting, especially for data regions. For example, over the past 40 years, the mean discharge of the Paraná River in Brazil has increased notably (+11.1% in the 1980s, +18.0% in the 1990s, and +6.3% in the 2000s) with no evidence of significant increase in rainfall over this period. Lee *et al.* (2018: *Regional Environmental Change*) examined the mechanistic linkages between climate variability, land-use, and resulting river discharge in the Paraná River basin using a terrestrial biosphere model that was evaluated against the natural flows at Itaipu and the regional total water storage (TWS) change from GRACE products. They found that the observed multi-decadal increase in discharge can be explained by concomitant changes in land cover that have occurred within the basin during this period. Their analysis also indicates that the peak discharge timing may have shifted concurrently from January/February in the 1970s to March in more recent decades. While land-use effect dominantly alters the long-term temporal dynamics of the river discharge over multi-decades, the change in the seasonality of the discharge can be attributable to the combined effect of the land-use and climate variability. This study suggests that the mean annual discharge is likely to change in the other South American River basins where land transformation is currently taking place, and the shift of the month of peak discharge needs to be taken into consideration to forecast the hydropower generation under changing climate and land conversion.

Soil moisture

Soil moisture is the vital connector between surface water and groundwater and it influences precipitation runoff, snowmelt volumes, and many fluvial hazards. Soil moisture is also the interface between water and plants for many ecosystems making it an important connection between the water, energy, and carbon cycles. The launch of SMAP in 2015 has made it possible to begin to address global soil moisture issues, with some of the first results being published this year. Similarly, as algorithms improve for analyzing GRACE data, it is becoming possible to better characterize soil moisture contributions to GRACE time-series data. This section outlines innovative research that utilizes SMAP data to estimate landscape soil water loss; tcombines SMAP and precipitation data to assess variability in hydrological storage length scales; and analyzes GRACE data to improve soil moisture and groundwater estimations.

Early work by Akbar *et al.* (2018b: *Journal of Hydrometeorlogy*) developed a loss function that uses SMAP soil moisture to describe the movement of water through the top soil. Though SMAP senses only the top 5 cm of soil, the loss function highlights the role of this thin layer in multiple earth system processes and the study team have applied it to delineate areas of the CONUS based on the relative roles of drainage and evaporation, whether it is water or energy limited. Results have also shown median decay time scales gradually increase with increasing wetness, from approximately 3 days in hyper-arid regions to seven days in more humid areas. These are typically faster than previous analysis of soil moisture time scales (i.e. Studies of memory and persistence) in part due to the focus on the thin upper layer as opposed to the larger root-zone soil moisture use in most previous studies. The results presented on regime type may help early identification of departure from normal conditions for a region and possible initiation of a flash drought (or the end of a drought).

Akbar *et al.* (2018a: *Water Resources Research*) combined SMAP data with precipitation from the gauge-corrected Climate Prediction Center daily global precipitation product to examines the characteristic length scale, or effective depth Δz, of a simple active hydrological control volume, where the volume is described only by precipitation inputs and soil water dynamics evident in surface-only soil moisture observations. They found that the length scale Δz exhibits a clear east-west gradient across the contiguous United States (CONUS), such that large Δz depths (>200 mm) are estimated in wetter regions with larger mean precipitation. The median Δz across CONUS is 135 mm. The spatial variance of Δz is predominantly explained and influenced by precipitation characteristics. Soil properties, especially texture in the form of sand fraction, as well as the mean soil moisture state have a lesser influence on the length scale.

Tangdamrongsub *et al.* (2018: *Hydrology and Earth System Sciences*) combines GRACE's least-squares normal equation (obtained from ITSG-Grace2016 product) with the results from the Community Atmosphere Biosphere Land Exchange (CABLE) model to improve soil moisture and groundwater estimates. Their approach is applied to estimate the soil moisture and groundwater over 10 Australian river basins and validated against the satellite soil moisture observation and the *in situ* groundwater data. By comparing their results to CABLE, they demonstrated that their innovative approach delivers evident improvement of water storage estimates, consistently from all basins, yielding better agreement on seasonal and inter-annual timescales. Significant improvements are also found in groundwater storage while marginal improvements are observed in surface soil moisture estimates.

Groundwater

Measuring groundwater is challenging in localized basins, let alone on global scales. There are currently two remote sensing approaches for measuring and tracking changes in groundwater. Interferometric Synthetic Aperture Radar (InSAR) 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. Historic GRACE data and anticipated data from 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 following two studies summarized analyze changes in groundwater using GRACE data.

Accurate knowledge of groundwater storage variation (ΔGWS) is important to understand regional groundwater availability and sustainability, especially in arid environments with limited surface water recharge potential or climatic variability. Tangdamrongsub *et al.* (2018: *Remote Sensing*) evaluated the ΔGWS computation from four state-of-the-art land surface models and GRACE data assimilation in Australia and the North China Plain. They found that that the inclusion of GRACE data in their models improved the ΔGWS estimates for both seasonal and long-term groundwater variations was in good agreement with groundwater records from deep aquifers in both study areas and resolved significant anthropogenic groundwater depletion. Furthermore, the inclusion of GRACE data also improved the estimation of groundwater depletion that the models could not accurately capture due to the incomplete information of the groundwater demand, or the unavailability of a groundwater consumption routine. The inclusion of GRACE data significantly improved their groundwater models.

The coarse spatial resolution of GRACE products has limited its functionality and integration into local groundwater resource assessments and water management models. Yin *et al.* (2018: *Journal of Geophysical Research: Atmospheres*) developed a statistical downscaling methodology that can be applied only in areas where there is a strong relationship between GRACE-derived groundwater storage (GWS) and ET at different spatial scales. Their approach used three ET data sets (GLEAM, NoahV2, and MOD16) to downscale GRACE groundwater storage anomalies (GWSA) from the spatial resolution of 1° to 0.25° (110 km to 2 km) in the North China Plain between 2003 and 2014 and they successfully measured subgrid heterogeneity in groundwater storage changes that were validated using data from 111 observations. Their results showed nominal errors in downscaled GWSA when integrating all three ET data sources, with uncertainties ranging from 4% to 15%. Their approach has significant applicability of downscaling GWA in area regions where the variability of ET can be resolved at different spatial scales, thereby providing a new tool that greatly enables the usability of GRACE data to better characterize/measure groundwater at much finer scales that has been currently possible and cold be readily integrated into the management of local water resources.

Global precipitation, evaporation, and the cycling of water

The WEC 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.

Every satellite mission has a calibration and validation plan to ensure that the satellites are accomplishing their research objectives. The Olympic Mountains Experiment (OLYMPEX) is a ground validation field campaign designed to verify and validate satellite measurement of precipitation from the constellation of satellites known as the Global Precipitation Measurement (GPM). The primary goal of OLYMPEX (October 2015 to 30 April 2016) was to validate rain and snow measurements in midlatitude frontal systems moving from ocean to coast to mountains and to determine how remotely sensed measurements of precipitation by GPM could be applied to a range of hydrologic, weather forecasting and climate data. OLYMPEX used a multi-observational approach that included the temporary installation of 120 precipitation gages to estimate daily and finer-scale precipitation at the spatial resolution of 1/32° at a variety of elevations. Chao *et al.* (2018: *Journal of Hydrometeorology*) collected SWE measurements with JPLs Airborne Snow Laboratory (ASO) during OLYMPEX, compared their results with both IMERG (version 04A) and its Japanese counterpart GSMaP's (version 04B) and found that both satellite products underestimate winter precipitation by 41% and 28%. They also found that the underestimation is more pronounced for the orographically enhanced mountainous interior of the OLYMPEX domain, by 57% and 48%, respectively. In contrast, IMERG and GSMaP storm interarrival time statistics are quite similar to those estimated from gridded observations.

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. Below are two 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.

Given the significant role ARs play in extreme weather (precipitation, floods, wind) and water supply, it is important to develop insight into how these extremes may change in the future: two noteworthy studies are described here. Espinoza *et al.* (2018: *Geophysical Research Letters*) used historical and RCP8.5 CMIP5 simulations from 21 models to quantify projected changes to AR frequency, strength, length and width for the late 21st century and found that there will likely be ~10% fewer ARs in the future, the ARs will be ~25% longer, ~25% wider, and exhibit stronger integrated water vapor transports (IVTs) under RCP8.5. These changes result in pronounced increases in the frequency (IVT strength) of AR conditions under RCP8.5 of about ~50% (25%) globally. DeFlorio *et al.* (2018: *Journal of Hydrometeorology*) assessed if the state-of-the-art operational model ensemble hindcast system (ECMWF) can predict the occurrence of AR with sub-seasonal lead times? They found that the ECMWF outperforms the reference forecast based on monthly climatology of ARiwk occurrence with 1-week, 2-week, and 3-week lead for ARs over the North Pacific/Western United States. They also found statistically significant increases in AR 1-week occurrence forecast skill (either at or near 95%) are seen during MJO Phase 8 relative to all NDJFM days with a 2-week lead. The significance of this study is that it is now be possible to forecast AR with 1-3 weeks lead-time, which will be invaluable for decision makers and resource managers (e.g. water resources and hazard response).

Water – Ecosystem / Vegetation / Drought

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 two studies below are advancing our understanding about the water-ecosystem/agriculture interface during droughts and in semi-arid ecosystems.

The amount of evapotranspiration in the Sierra Nevada mountains is important because this water is not available for downstream uses, supports alpine ecosystems, and may change in a future climate. Currently there are few measurements of evapotranspiration in the Sierra Nevada across a diverse landscape. Henn *et al.* (2018: *Water Resources Research*) combined data from the JPLs Airborne Snow Observatory (ASO) with multiple stream gauge observations from Yosemite National Park to estimate evapotranspiration using a water balance approach during the 2013–2015 California drought and found that evapotranspiration averages 162–191 mm per year, over the time period from peak snowpack in the spring to the end of the summer. When these results were compared with other estimates of evapotranspiration, they found that the estimates were smaller, perhaps due to the diverse spatial terrain sampled by this approach. They also found that the estimates vary only slightly from year to year during the California drought. This study may help understand how evapotranspiration, and thus available water supply, may change in a warmer future climate.

Another study that also utilized lidar data from ASO sought to assess how well lidar data could be used to accurately characterize vegetation in semi-arid environments, often where vegetation close to the ground surface. Ilangakoon *et al.* (2018: *Remote Sensing of Environment*) exploited ASO's small footprint, full waveform lidar capabilities to assess classification performance of six major plant functional types (PFT), including 36 shrubs and trees, along with bare ground in the Reynolds Creek Experimental Watershed, Idaho. They derived waveform features at two spatial scales (1 m and 10 m) by applying a Gaussian decomposition and a frequency-domain deconvolution and employed an ensemble random forest algorithm assess classification performance and to select the most important waveform features. They found that the 1 m resolution lidar height features improved the PFT classification accuracy by 10%. One of the significant findings from the study was that bare ground was clearly differentiated from shrubs using pulse width, which is important in semi-arid ecosystems.

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. Multi/hyperspectral optical remote sensing approaches, such as MODIS and ESA's MERIS sensors, enable the broad scale assessment of water quality through the detection and tracking of water properties. The Wang *et al.* (2017) study below develop a new approach to track harmful algal blooms (HAB) in Lake Erie where Ortiz *et al.* (2017) evaluates different atmospheric correction methods specifically targeted at improving remote sensing characterization of HAB.

Optical properties of phytoplankton, specifically the absorption coefficients of the pigments inside them, play a key role in determining both the penetration of radiant energy in water and the use of this radiant energy for photosynthesis. These pigment absorption coefficients and their concentrations are important for understanding photosynthetic rate, identifying and quantifying phytoplankton functional groups, and determining size class distributions. Wang *et al.* (2017: *Remote Sensing*) incorporated a Gaussian curve scheme derived from MERIS and MODIS hyperspectral images into a semi-analytical model to detect and track chlorophyll *a* and phycocyanin concentrations in Lake Erie in 2014 and obtained seasonal variations of Gaussian absorption properties in 2011 with MERIS imagery. This study shows that it is feasible to obtain Gaussian curves from multi-spectral satellite remote sensing data, and the obtained chlorophyll *a* and phycocyanin concentrations from these Gaussian peak heights demonstrated potential application to monitor harmful algal blooms (HABs) and identification of phytoplankton groups from satellite ocean color remote sensing semi-analytically.

A fundamental challenge associated with analysis of multispectral and hyperspectral visible remote sensing imagery is removal of atmospheric effects, especially when extracting which constituents are present during Cyanobacterial Harmful Algal Blooms.

Ortiz *et al.* (2017, *Frontiers in Marine Science*) explore several different empirical methods of atmospheric correction, which enables extraction and separation of mixed environmental signals from aquatic data sets. They develop an innovative calibration approach that employs a floating panel (1.07 m by 1.17 m; 1.25 m^2) composed of 16 convex mirrors (0.26 m diameter with radius of curvature 0.18 m) deployed on the water surface, providing an in-scene lake surface reference for image reflectance factor calibration. They found that three of the four methods of calculating reflectance factors produced a random noise component, with the largest spectral response in the blue end of the spectrum and near zero responses at other wavelengths. This spectral and spatial pattern is consistent with path radiance effects that likely arise from ancillary calibration data that are not precisely temporally or spatially coincident with the observations. The development of atmospheric correction methods that are effective is important to enable optimal use of future, planned hyperspectral orbital missions, such as PACE, HyspIRI, GeoCAPE, and the Decadal Survey's Surface Biology and Geology.

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FY 2018 Annual Performance Indicator	FY 15	FY16	FY17	FY18
ES-18-7: 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.	Green	Green	Green	Green

Annual Performance Indicator ES-18-9: 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.

Research supported by NASA's Climate Variability and Change (CVC) focus area increases our knowledge of global climate and sea level on seasonal to decadal time scales. Through a wide range of interdisciplinary projects, CVC supports the collection and assessment of satellite, aircraft and ground-based observations of the global ocean, sea and land-based ice, and their integration into comprehensive, interactive Earth system models. Highlights of results published this past year are summarized herein under seven major sections, as follows:

- Sea Ice in the Earth System
- Land Ice and Sea Level Change
- Oceans in the Earth System
- Ocean-Atmosphere Interactions
- Ocean-Hydrology Interactions
- Ocean-Land-Atmosphere-Solid Earth Interactions
- Earth System Model Improvements

Sea Ice in the Earth System

Sea ice plays a critical role in the Earth system by both reflecting solar radiation and regulating the transfer of heat and momentum between the atmosphere and ocean (Parkinson, 2018).

Overall, research in the last year focused on continued monitoring and interpretation of sea ice extent, thickness, and other characteristics (Comiso et al., 2017; Onarheim et al., 2018; Koyama et al., 2018; Nihashi et al., 2018; Peng and Meier, 2017) in the context of improving knowledge of the couplings among the ice, ocean, and atmosphere; as well as improved forecasts (Petty et al, 2017; Serreze and Meier, 2018). In addition, there was intense focus on preparation for the launch of ICESat-2 in September, especially through quantification of the thickness of snow accumulating on sea ice, an important parameter for both sea ice research and Earth system models (e.g. Kwok et al., 2017).

Update on sea ice extent

NASA continued studies of sea ice extent based on the passive microwave record, which included studies for improvements to current methods and ways to continue the record as the Defense Meteorological Satellite Program (DMSP) era comes to a close (e.g. Duncan et al., 2017 and Meier and Ivanoff, 2017). Sea-ice extent is reported routinely by NASA through the Arctic Sea Ice News & Analysis (ASINA) website hosted by the National Snow and Ice Data Center (NSIDC) (http://nsidc.org/arcticseaicenews/) and through support of researchers that contribute to NOAA's Arctic Report Card (http://www.arctic.noaa.gov/Report-Card). The ASINA website continues to be the primary reference for researchers, the media, and the general public (e.g. https://www.scientificamerican.com/article/arctic-sea-ice-is-getting-younger-here-is-why-that-is-a-problem/). The 2017 Arctic sea-ice minimum extent was recorded on September 13, 2017 at approximately 4.64 million square kilometers (1.79 million square miles), the eighth-lowest in the 38-year satellite record (https://nsidc.org/news/newsroom/arctic-sea-ice-minimum-extent). The winter maximum for 2018 was similarly low at an extent of 14.48 million square kilometers (5.59 million square miles). This value, recorded on March 17, 2018, was is the second lowest in the 39-year satellite record, falling just behind 2017 (http://nsidc.org/arcticseaicenews/2018/03/arctic-sea-ice-maximum-second-lowest/). The age and thickness of sea ice is also changing, and 2018 saw the lowest extent of ice greater than five years old (http://nsidc.org/arcticseaicenews/).

Sea ice in the Southern Ocean underwent a startling transition in 2017 from increasing (Comiso et al., 2017) to decreasing extents. These trends are considered in detail in a 2017 report by the *National Academy of Sciences, Engineering Medicine* on Southern Ocean sea ice, which notes that the controls on its extent remain poorly understood (NASEM, 2017).

Characterizing sea ice properties

Research using satellite altimetry to study sea ice thickness continued to track ice age and volume (Nihashi et al., 2018) and to prepare for the launch of ICESat-2 (https://icesat-2.gsfc.nasa.gov/) in September, 2018. As ICESat's (https://icesat.gsfc.nasa.gov/) planned successor, ICESat-2 is optimized to measure global sea ice freeboard and the heights of the Antarctic and Greenland ice sheets using a multibeam, photon-counting instrument. Publications were released on the mission's science goals (Markus et al., 2017), instrument details (Bae and Webb, 2017), observation methods (Magruder and Brunt, 2018), science algorithms and laser altimetry (Popescu et al., 2018; Brunt et al., 2017; Sun et al., 2017) and outreach (Casasanto and Markus, 2017).

Related to ICESat-2, an important developing area of research is snow on sea ice. Snow thickness is critical to interpreting satellite altimetry measurements (Kwok and Markus, 2017), as well as validation of precipitation over polar regions for Earth system models (Blanchard-Wrigglesworth et al., 2018). The snow radar observations from NASA's IceBridge mission are being assessed with new algorithms (Kwok et al., 2017) and in situ methods (Haas et al., 2017) to determine how well satellite reanalyses such as NASA's MERRA-2 and other methods estimate polar precipitation. Using a reanalysis-based snow depth reconstruction, Blanchard-Wrigglesworth et al. (2018) found that the relationship between snow depth and first year vs. multi-year ice observed in the western Arctic is not seen in the eastern Arctic indicating that the weighted climatology commonly used to calculate sea-ice thickness may be biased.

Quantifying connections between sea ice and the ocean and atmosphere

While sea ice models are far from reproducing sea ice trends, NASA supports work that will ultimately improve their sophistication and predictive skill. A nagging question in sea ice research is determining the specific mechanisms of ice loss (Stroeve et al., 2018).

New constraints on sea ice transport and export (Smedsrud et al. 2017; Tooth and Tschudi, 2017 and 2018) are being developed, with ever more detailed work on the couplings of the ice to the ocean (Armitage et al., 2018; Dewey et al., 2017; Spreen et al., 2017; Kwok et al., 2017) and atmosphere (Kwok et al., 2017; Taylor et al., 2017) including the radiative balance (Smith et al. 2017) and winter warming (Graham et al., 2017). For example, Smedsrud et al. (2017) shows the export of sea ice through the Fram Strait has increased in the past few decades due to stronger southward geostrophic winds caused by increased surface pressure over Greenland.

Land Ice and Sea Level Change

Loss of ice from Greenland and Antarctica, as well as the Earth's smaller glaciers and ice caps, contribute to global sea level rise. Characterizing these contributions and the processes that govern them continues to be a major focus of the program.

The most important result this year is the assessment from the NASA-ESA Ice Sheet Mass Balance Intercomparison Project (IMBIE) which demonstrated--from a comprehensive suite of satellite measurements--that Antarctica is losing mass overall and that East Antarctica is in balance to within measurement uncertainties (Shepherd et al., 2018). The East Antarctic result is particularly important, because previous assessments had yielded contrasting estimates. Consistent with this result, Gardner et al. (2018)--using Landsat imagery--showed increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years, which became one of the journal's most downloaded papers.

Greenland also continued to lose mass over 2016, with near-record-setting melting occurring earlier and over a larger area than the 1979-2016 average (Tedesco et al., 2017). New global assessments of glacial isostatic adjustment from GRACE are improving assessments of ice mass loss (Caron et al., 2018). Major improvements in maps of Greenland topography and bathymetry were seen with the release of BedMachine v3 which revealed that the total sea level potential of the Greenland ice sheet is 7 cm greater than previously estimated (Morlighem et al., 2017).

Sea level attributions, assessments and projections continue to improve (Shepherd and Nowicki, 2017). Coastal planners now have access to tools to consider how non-uniform rise will impact their specific coast (Hsu and Velicogna, 2017; Larour et al., 2017). Ice sheet models are being improved through intercomparisons (Goelzer et al., 2018), development of higher resolution models (Cuzzone et al., 2018) and consideration of local geologic phenomena, such a mantle plume heating (Seroussi et al., 2018).

Production of more detailed bed maps (An et al., 2017; An et al., 2018; Bingham et al., 2017; Jordan et al., 2017; Millan et al., 2018; Schroeder et al., 2017) is also improving models, as are improved knowledge of glacial dynamics. Comprehensive mapping of ice flow and velocity changes were published for Greenland (Joughin et al., 2018; Joughin et al., 2017; Kehrl et al., 2017) using InSAR, and improvements were made to the ionospheric corrections (Liao et al., 2018). Mass transport waves amplified by intense Greenland melt were detected in solid Earth deformation through an innovative approach using GPS stations (Adhikari et al., 2017). The role of the basal thermal state on ice sheet stability was examined by Chu et al. (2018).

Quantifying connections between land ice and the ocean

Details of ice-ocean interaction continue to be revealed, and in the last year new approaches to both quantification and characterization of the processes were developed. Overall links between tides and the ice sheets were reviewed in Padman et al. (2018) with recommendations on the data needing to be acquired to ascertain tidal effects. For Greenland, parameterizations of fjord thermal energy fluxes demonstrated the critical role of fjord-glacier geometry (Carroll et al., 2017) and discharge plume dynamics (Jackson et al., 2017). Choi et al. (2017) demonstrated how differences in geometrical setting modulate response to oceanic warming for two glaciers in Northeast Greenland.

For Antarctica, impacts of tides on the Filchner-Ronne shelf were reviewed in Mueller et al. (2018), who projected increased heating and melting. A fully coupled ice-ocean model better reproduced the observed retreat of Thwaites Glacier and projected continued mass loss at a sustained rate over coming decades (Seroussi et al., 2017). Nakayama et al. (2018) made improvements to ocean representation in modeling of ice-shelf ocean interactions. Cai et al. (2017) showed the importance of subglacial runoff critical to model ice shelf melt rate intensities beneath the Petermann Gletscher Ice Shelf.
New approaches to observing ice shelf changes included the following: basal melting from satellite altimetry by Adusumelli et al. (2018) that showed wide variation over short spatial scales; GPS reflectometry by Shean et al. (2017) that connected basal melting and ice-shelf features associated with extension; and satellite microwave studies by Alley et al. (2018) of the vulnerability of shelves to hydrofracture. Hogg et al. (2017) showed increased flow and ice discharge in Western Palmer Land, especially in areas with loss of buttressing from ice shelf thinning. Short-term grounding zone variability was examined by Milillo et al. (2017). Paolo et al. (2018) and Walker and Gardner (2018) noted correlations of the El Nino/Southern Oscillation with surface mass balance and basal melting. Minchew et al. (2018), Seroussi et al. (2017), Roberts et al. (2018), and Lilien et al. (2018) looked at the glacial dynamic response associated with ocean forcings on shelves and changes in grounding line location. Millan et al. (2017) improved sub-ice shelf bathymetry in West Antarctica, finding previously unknown deep channels reaching glacier grounding lines. Yu et al. (2017) examined different modeling methods to represent calving, finding that capturing the stress field near the grounding line is critical. But not all areas of Antarctica are changing, and Fountain et al. (2017) showed that

glacial responses around Antarctica are not uniform, with glaciers and ice tongues along the western Ross Sea showing little change.

Finally, Wagner et al. (2018) offered a unique insight into how icebergs survive long ocean voyages during Heinrich events by inducing growth of sea ice buffers.

Surface mass balance and sub- and supraglacial water

Surface properties of the Greenland Ice Sheet were assessed in a range of studies. Overall, a Greenland-wide Earth System Data Record was produced to meet the needs of ice sheet modelers (Hall et al., 2018). Specific assessments were also performed for precipitation for Greenland (Berdahl et al., 2018), including near surface temperature records (Adolph et al., 2018; Hearty et al., 2018) and snow density (Fausto et al., ,2018). Surface albedo for Greenland was assessed at more detailed levels with characterization of surface ablation (Moustafa et al., 2017) and local variability (Ryan et al., 2017; 2018).

Surface meltwater runoff in Greenland was measured directly by Smith et al. (2017). Drivers and relationships to climate factors were examined for the atmosphere (Cullather and Nowicki, 2018) and sea ice extent (Stroeve et al., 2017). Meltwater retention was parameterized for both firn and firn aquifers (Steger et al., 2017; Legchenko et al., 2018; Miller et al., 2017) as well as the ablation zone (Cooper et al., 2017).

In Antarctica, snow accumulation was measured by GPS reflectometry (Siegfried et al., 2017). Subglacial lakes in Antarctica were shown to be highly dynamic over decadal timescales (Siegfried and Fricker, 2018) with links to ice stream dynamics (Dow et al., 2018) and ice sheet flexing (Walker et al., 2017).

Non-Polar Land Ice

Publications on non-polar glaciers had a range of foci. Globally, Huss and Hock (2018) projected the hydrological response to future glacier mass loss. For Alaska, mass balance histories were developed for various Alaskan glaciers (Young et al., 2018; Roth et al., 2018; Kienholz et al., 2017).

For Asia, NASA’s HiMAT (High Mountain Asia Team) program entered its second year with the publication of various results. Most importantly, Shean (2017)--in three separate publications--developed the first, broad-scale high-resolution digital elevation models for the High Mountain Asia (HMA) region from stereo satellite imagery. Olson and Rupper (2018) offered new detail on the impact of shading on HMA surface mass balance. Rainfall-triggered landslide hazards for HMA and the rest of the globe were assessed by Kirschbaum and Stanley (2018). Rounce et al. (2018) created a new approach to assessing challenging debris-covered glaciers and Haritasha et al. (2018) studied the controls on glacial lake formation and evolution, critical to hazard assessment for glacial outburst flood events. This article was highlighted in AGU's EOS as a research spotlight on May 29, 2018 (Cook 2018).

Data for the HiMAT team and global glaciers is stored at the National Snow and Ice Data Center (NSIDC), a NASA Distributed Active Archive Center (http://nsidc.org/data/highmountainasia). There were a number of new contributions for 2018. In addition to contributions from the HiMAT investigators, the Global Land Ice Measurements from Space (GLIMS) team added more data for glaciers in Austria, Arctic Canada, Irian Jaya (Indonesia), Svalbard (Norway), Patagonia, and Washington State's Olympic Peninsula (http://www.glims.org). In addition, the Randolph Glacier Inventory (RGI) Working Group released Version 6.0 of the RGI on 2017-07-28 (http://www.glims.org/RGI/index.html), which is a critical dataset for work of the Intergovernmental Panel on Climate Change (IPCC).

Oceans in the Earth System

Oceans play a fundamental role in the Earth's system, modulating our planet's climate and weather by storing and transporting large quantity of heat, water, and carbon dioxide, as well as exchanging these elements with the atmosphere. This continuous exchange of properties influences climate and weather patterns over the globe by releasing the heat that fuels the overlying atmospheric circulation, releasing aerosols that impact cloud cover, absorbing and storing atmospheric carbon dioxide for millennia, and by releasing moisture that determines the fate of the global hydrological cycle.

During this year, NASA Physical Oceanography (PO) Program continued supporting a wide range of studies that quantify the ocean's role in the climate system through the ocean's dynamical and thermodynamical processes, the ocean's system-to-system and multi-disciplinary interaction within the complex ocean-atmosphere-land-solid Earth system. Below are the most notable discoveries in 2017- 2018 that were supported by NASA PO.

Ocean dynamics drive climate variability

Ocean currents displace and transport water by the fluid's organized velocity field, affecting fluid properties, such as temperature, salinity, oxygen, etc. New studies continue to provide evidence of the importance of ocean dynamics in climate variability. Piecuch et al. (2017) explains the reversal of decadal trends at the ocean surface in the North Atlantic that flipped from warming to rapid cooling – a phenomenon labeled "the cold blob" in popular media, referring to a dramatic transformation of surface waters in the subpolar gyre. They conclude that the ocean heat advection is the primary contributor to the trend reversal, emphasizing the relative role of ocean circulation compared to other factors, such as anthropogenic aerosols and surface air-sea flux. Accounting for ocean dynamics has been also critical in explaining transport anomalies in the Atlantic (Roberts et al., 2017; Grodsky et al., 2017) and Pacific oceans (Qiu et al., 2017), and is essential to predicting skills of sea level change over the globe (Sonnewald et al., 2018), ocean basins (Volkov et al., 2017), and coastal boundaries (Minobe et al., 2017). Explicit inclusion of variable ocean circulation has further implications in predicting the global mean temperature and the planet's mean surface climate (Ponte and Piecuch, 2018).

Besides redistribution of heat, another way that oceans affect the Earth's climate involves the mixing of heat anomalies throughout the water column, which slows down the rates of surface warming. Mixing can be performed by small-scale oceanic processes, known as diapycnal and isopycnal diffusion, meso- and submesoscale eddies, and convection. New results by Liang et al. (2017) determine substantial contribution of small-scale mixing processes to heat exchange between the upper and deep oceans on decadal scales. Investigations on ocean mixing is a new focus area for NASA PO program – stay tuned for more discoveries in the upcoming years.

In addition to heat fluxes, the ocean's dynamics also influence climate variability through salt fluxes. Evidence from NASA data and models suggest that in response to the warming climate, there has been an amplification of the ocean water cycle in the past two decades, where ocean's dry areas are becoming drier and wet areas are becoming wetter. Vinogradova & Ponte (2017) demonstrate the importance of ocean circulation in blurring the atmospheric signatures through salt flux convergences. Ocean dynamics, therefore, effectively compensate atmospherically-imposed pattern amplification, buying us time before we will see the full impact of the amplified water cycle at the ocean surface.

Warming oceans melt land ice

Growing evidence suggests that warming ocean temperature around Greenland and Antarctica may be responsible for accelerated ice loss. Willis et al. (2018) uses observations of temperature and salinity from NASA's Oceans Melting Greenland (OMG) mission to illustrate how vigorous entrainment of warm subsurface water causes accelerated mass loss, thinning, and retreat of a glacier in northwest Greenland. Similar to Greenland, the ocean's destabilizing effect on land ice sheets is also evident in Antarctica. Alley et al. (2018) identifies ocean warming as a primary contributor to the failure and eventual breakup of the Antarctic ice shelf, and ocean circulation as the main control in the distribution of melt waters within the Antarctic shelves. Their conclusions agree with those of Shepherd et al. (2018) who identify the oceans as a continuing destabilizing influence on the shrinking ice shelves in Antarctica.

Ocean-Atmosphere Interactions

While primarily it is the atmosphere that drives the ocean through the exchange of momentum, heat, and water vapor at the air-sea interface, in vast ocean regions the ocean exerts a strong feedback on atmospheric motion. Examples are the tropical and equatorial ocean regions that are known for the intense exchange of heat at the surface boundary, and where interannual to decadal climate variability is linked to coupled ocean-atmospheric modes. The influence of most prominent ocean climate cycles such as ENSO, PDO, NAO, and MJO is well publicized and often linked to weather anomalies on land. Understanding and predicting these climate modes is one of the priorities for NASA PO and involves improved understanding of ocean-atmospheric coupling, enhancing our existing tools, and exploring novel approaches in air-sea exchange monitoring.

Toward better characterization of ENSO events

NASA Earth observing satellites continue to monitor ENSO events in the ocean using a variety of observations, by tracking the movement of warm water in the tropical Pacific using temperature data from Aqua satellites, and by observing the weakening of the Pacific trade winds and sea level rise from Jason missions. Combined with numerical simulations, these observations give insights into the stochastic nature of the tropical climate system. One open question is understanding the different flavors of ENSO events and their distinct precursors, including the highly publicized "failed" event of 2014, when a weak, almost uniform warming event developed by year-end, contrary to the broadly anticipated El Nino by a large ensemble of climate models. Hu and Fedorov (2018) demonstrate that the El Nino development in 2014 was impeded by exceptionally strong easterly wind bursts that occurred sporadically in the equatorial Pacific. Further, the failed event in 2014 allowed for the ocean heat content to recharge, preconditioning the ocean-atmosphere system for the development of an extreme warm El Nino in 2015.

In addition to the traditional use of temperature and wind data, the use of salinity observations has emerged as a promising tool to understand and expand the limits of ENSO prediction. Hackert et al. (2017) assimilated satellite salinity measurements from Aquarius, SMOS, and SMAP into an ocean-atmospheric coupled model and demonstrated that accounting for salinity structures improves ENSO's prediction skill. In particular, salinity data provide powerful constraints to fluxes of freshwater across the air-sea interface. That includes constraining precipitation fluxes that, if unconstrained, suffer from large uncertainties in coupled models and impact forecast accuracy. Salinity information also improves the representation of mixed layer dynamics, mainly by constraining barrier layer thickness which acts to inhibit entrainment of deeper, colder, and saltier water into its case; this, in turn, impacts the efficiency of ENSO coupling.

Predicting MJO and Indian Monsoons using ocean observations

Another tropical ocean-atmospheric phenomena highlighted this year refers to the Madden-Julian Oscillation (MJO), which describes a periodic, eastward moving progression of rain, winds, and pressure over the equatorial and tropical Indian and Pacific Oceans. Analogous to ENSO for seasonal forecasts, MJO is recognized as one of the leading sources of predictability for sub-seasonal forecasts, including extreme heat waves, atmospheric rivers, and Indian Monsoons. Recent studies show that skillful prediction of the MJO passages and Indian Monsoons critically depend on the ability of forecast models to capture the oceanic influence. Ocean feedback and coupling mechanisms are linked to the ocean's intrinsic climate variability (Han et al., 2017; Krishnautri et al., 2017), upper-ocean temperature, salinity, and stratification (Li et al., 2017a, b), and the ocean's dynamics in a form of Equatorial Rossby waves and Equatorial surface currents, as well as vertical advective heat fluxes (Delman et al., 2018).

Satellite ocean winds explain climate variability

Paramount to our understanding and forecasting of the ocean-atmosphere interaction is the accurate knowledge of surface winds over the oceans. NASA-PO continues supporting a wide range of oceanographic, meteorological, climate, and interdisciplinary science applications derived from Earth-observing missions carrying scatterometers and polarimetric radiometers.

Coming to a decommission this fall, QuikSCAT is ending its successful mission, establishing one of the longest climate data records by a single spaceborne instrument and providing crucial ocean vector winds data. The data enabled discoveries of new mechanisms of air-sea interaction, improved forecasting of tropical hurricanes and cyclones, and allowed us to monitor ongoing changes of the Earth's systems, including sea ice, land and snow cover, urban extent, carbon biomass, and ocean productivity. The long duration of the QuikSCAT mission also enabled the development of the first global climatologies of winds over the ocean at high spatial resolution.

Taking advantage of the QuikSCAT data, Stephens et al. (2017) discovered a coupled dynamical-radiative feedback over the wet ITCZ region that can explain the intensification of the hydrological cycle in the tropics at rates larger than expected from the classic Clausius-Clapeyron theory. The positive feedback leads to an increase in precipitation during ENSO-related warming of the ocean surface, and has potential applications in the prediction of change in precipitation patterns in response to the warming oceans.

Wind climatology also helps determine the linkage between wind forcing, ocean upwelling, and ocean productivity. Fewings (2017) used QuikSCAT wind products to show that the wind variations along the California Current are not random as previously thought, but form a coherent dipole pattern extending along the entire west coast of the United States – changing our understanding of the winds that drive the highly productive coastal regions and explain coastal upwelling anomalies and marine heat waves.

New and improved approaches to measure ocean winds from space

Continuous improvement and enhancement to the surface ocean wind products is ongoing, expanding the range of data applications and its user-base. Recent examples include the production of a new satellite dataset with the capability to measure hurricane-force winds based on SMAP observations (Meissner et al., 2017), which is currently used in forecasting of tropical cyclones; creating best practices in using wind forcing in ocean-ice coupled systems (Dukhovsky et al., 2017); and ensuring consistency in scatterometer-derived vorticity (curl of the ocean surface vector winds) across swaths and between the platforms (Holbach et al., 2017).

Conceptually novel approaches to measure winds from space are being explored, and involve a concurrent observations of ocean winds and currents. Surface winds drive ocean circulation both locally (through Ekman dynamics) and remotely (through planetary waves). Current satellite technologies from satellite altimetry provide observations of planetary wave propagation and geostrophic currents, missing a large ageostrophic component of surface currents. A new study by Rodriguez et al. (2018) advances the theory and techniques to concurrently measure winds and currents from space in support of a potential future air-sea interaction mission discussed by the National

Academies of Sciences in their recent Decadal Survey. Having global, collocated observations of ocean currents and winds will provide the next major step forward in understanding the dynamics of the upper ocean and its coupling to the atmosphere, thereby improving and constraining future models of climate variability and change.

Ocean-Hydrology Interactions

Containing 97% of the Earth's water, exchanging 80% of all freshwater fluxes at its surface, and being the ultimate source of all terrestrial water, the ocean is the best place to ascertain ongoing changes in the global hydrological cycle, including its terrestrial component. Recent studies supported by NASA PO quantify how the changes over the ocean, including recent amplification of the ocean water cycle, are linked to terrestrial flood events and heavy rainfall powerful enough to reshape the coastline of the United States and Europe.

Predicting land precipitation using ocean salinity

The contribution of the oceanic water cycle to terrestrial hydrology is most significant in the variability of precipitation over land, including hydroclimate extremes such as floods, drought, and water shortage. As freshwater leaves or enters the ocean via the processes of evaporation, precipitation, and runoff, it makes a fingerprint detectable in ocean variables, including ocean salinity. A new study by Li et al. (2018) demonstrates how the use of sea surface salinity improves predictive skill of the extreme precipitation over the continental US, ranking salinity as the most important predictor compared to the other ten climate indices. Owing to its sensitivity to freshwater flux, salinity serves as an indicator of the ocean water cycle in the subtropical Atlantic, which plays the dominant role in sustaining the moisture supply over the mid- and south-western United States. Utilizing pre-season information of sea surface salinity in the subtropical ocean significantly improves AI-based rainfall prediction, including the record-breaking precipitation season and flood events of 2015.

Satellite salinity improves ocean-land linkages

Rivers provide the link between the oceans and the terrestrial water and bio-geochemical cycles. Salinity observations from SMAP and SMOS, together with land measurements, allow us to trace large riverine waters over great distances, and reconstruct the complete lifecycle of hydrological events, from rainfall to river discharge on land, and then to river plume formation, mixing, and advection in the ocean. In addition to tracing the origin and fate signatures of freshwater, satellite salinity measurements are also used to gauge the influence of rivers on regional climate and oceanic productivity (Fournier et al. 2017a), as well as the impacts of the river-influenced warming on the upper ocean during the Atlantic hurricane season (Fournier et al., 2017b).

Ocean-land-atmosphere-solid Earth Interactions

Significant progress in understanding the multi-disciplinary interactions within the complex ocean-atmosphere-land-solid Earth system has been made in the last year, supported by joint efforts between Physical Oceanography, Cryosphere, and MAP programs. The highlights from two main areas - sea level change and ocean state estimation for climate research – are highlighted below.

Sea level rise and acceleration

Satellite and in situ measurements detect a global (Nerem et al., 2018) and regional (Davis and Vinogradova, 2017) acceleration of sea level rise over the past two decades, commemorating 25 years of satellite altimetry. The rate of global sea level rise acceleration is estimated at 0.084 ± 0.025 mm/yr2, which, if coupled with the rate of ~3 mm/yr sea level rise, implies that the seas in 2100 could be 65 cm higher relative to 2005 if the observed changes are maintained over the next century. Regional acceleration can reach 0.3 ± 0.07 mm/yr2, but varies by location. The latter emphasizes an interplay between the changes in ocean dynamics, which dominate acceleration in the northeastern US, and the loss of ice mass, which accelerates sea level rise in the southern US. Here, Greenland and Antarctic influence alone could raise the seas by 0.75 meters over the next century, by changing the gravitational pull of ice. The need to account for the gravitational and loading effects of land ice on sea level is also supported by Ponte et al. (2018), who show improvement of quantitative interpretation of satellite altimeter observations for climate assessment purposes. Piecuch et al. (2018) use NASA satellite gravity measurements and ocean state estimates, along with coastal tidal gauge sea level data, to demonstrate the improved quality of recent NASA remotely-sensed ocean mass retrievals, which holds promise for better understanding of the nature of coastal sea level changes.

Ocean state estimates for climate research

Another inter-disciplinary area of research at ESD is to produce the best possible estimates of ocean circulation that can be used to assess the ocean's role in climate. Fukumori et al. (2017) describes a new release of the Estimating the Circulation and Climate of the Ocean (ECCO) solution of multi-decadal, global ocean state based on a variety of NASA observations (altimetry, SST, GRACE, Aquarius, etc.) and dynamical physical constraints. Due to its dynamical consistency and adjoint capabilities, ECCO continues to be a flagship ocean reanalysis, supporting a range of applications in climate research, including sea level and heat transport (Piecuch et al., 2017), global sea surface temperature (Ponte and Piecuch 2018), vertical heat redistributions (Liang et al., 2017), and high latitude and sea-ice dynamics (Jones et al., 2018). Recent studies position ECCO as a strong member within the global ocean synthesis and reanalysis system - an analog effort to CMIP initiatives and modeling experiments that are used in IPCC reports – highlighting ECCO's estimates of regional sea level (Storto et al., 2017), Arctic sea-ice covers (Chevallier et al., 2017), and mixed-layer variability and teleconnection patterns (Toyoda et al., 2017).

Earth System Model Improvements

CVC-supported Earth System Models

Models supported by the Modeling, Analysis and Prediction (MAP) program within the Climate Variability and Change 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.

Results from studies utilizing these and other MAP supported modeling efforts included:

Climate Modeling Advances

NASA climate modeling contributed to improved understanding of climate sensitivity this year, in particular the growing understanding that inferring climate sensitivity from recent observations could result in an incorrect estimate of climate sensitivity if recent observed climate variability is anomalous and not indicative of long-term response to climate forcing. Marvel et al. (2018) found that simulations constrained by historical SST values had a lower climate sensitivity than free-running simulations, resulting in the conclusion that the low estimates of equilibrium climate sensitivity from observations might simply be due to natural variability – that is, to chance.

Climate sensitivity in models depends in large part on the representation of climate feedbacks and climate processes in models. Substantial advances in these areas occurred in 2017. In a study of the reasons for intermodel differences in the global lapse rate and water vapor feedbacks, Po-Chedley et al. (2018) found that tropical surface warming leads to significant warming and moistening in the tropical and extratropical upper troposphere, signifying a nonlocal, tropical influence on extratropical radiation and feedbacks. However, they also showed that model differences in locally defined lapse rate and water vapor feedbacks, particularly over the southern extratropics, drive model variability in the global feedbacks.

Climate Process investigations included Adames et al. (2017), which investigated the processes that lead to changes in the propagation and maintenance of the Madden-Julian Oscillation (MJO) as a response to increasing CO_2 by analyzing moist static energy budget of the MJO in a series of NASA GISS model simulations. They found that changes in MJO propagation is dominated by several key processes, including horizontal moisture advection, found to be enhanced predominantly due to an increase in the mean horizontal moisture gradients, while MJO horizontal scale and the dry static stability were found to exhibit opposing trends that largely cancel out. They also noted that reduced sensitivity of precipitation to changes in column moisture also opposes enhanced propagation.

The issue of precipitation evolution in the MJO was addressed in Li et al. (2018), using three different cloud resolving models and comparing to observations taken during the Dynamics of the MJO (DYNAMO) field campaign. The results of these comparisons showed that Cloud Resolving Models (CRM) forced by large-scale forcing can reproduce not only common features in cloud populations but also variations observed by different radars. The study also noted some common deficiencies in the CRM simulations, which tended to underestimate radar echo-top heights for the strongest convection within large, organized precipitation features.

The representation monsoons and of processes influencing monsoons in climate models was addressed by Sharma and Miller (2017). The paper addressed the notion that dust radiative heating may influence monsoon precipitation on synoptic timescales, based on an observed correlation between AOD and monsoon precipitation over the Arabian Sea. The paper finds that the correlation occurs in Earth system models despite their lack of inclusion of dust radiative effects. It goes on to show that the correlation results instead from the effect of precipitation on dust concentrations, and concludes that the effect of dust radiative heating on synoptic monsoon precipitation remains unknown.
Prediction of ENSO tests our understanding of the factors causing ENSO variability in the Earth system. Huang et al. (2017) completed a set of 20-member ensemble seasonal reforecasts for 1958–2014 , with initialization in January, April, July, and October. This long dataset of reforecasts predicts more and diverse historical ENSO events and allowed the investigators the opportunity to examine the effects of multidecadal variability and climate change. ENSO prediction skills before and after 1979 were found to be comparable. This lack of significant improvement in skill after 1979, when many more observations for initialization were available compared to the pre 1979 period indicates that the predictions could have been compromised by model errors and deficiencies in the data assimilation systems, eliminating the benefit of increased numbers of observations. A tendency for overestimation of peak SST anomalies of strong El Nino events in NH fall-initialized simulations suggested that air-sea feedback in the eastern Pacific is overactive prior to ENSO event termination.

Clouds and Cloud Process Modeling Advances:
As mentioned above, the NU-WRF model is a regional-scale model supported by MAP to enable studies of climate processes at relatively high resolution compared to that possible from global model simulations. Iguchi et al. (2017) investigated the sensitivity of daily rainfall rates in regional seasonal simulations over the contiguous United States (CONUS) to four different cumulus parameterizations in addition to shallow cumulus representations, to understand how cumulus parameterization can affect precipitation predictions. It turns out that predicted precipitation depended more on the shallow cumulus component than the specific cumulus parameterization. Additionally, the spatial pattern of the seasonally averaged rainfall did not vary with cumulus parameterization over mountainous regions. However, precipitation over the Great Plains regions as well as the temporal variation over most parts of the CONUS sensitive to cumulus parameterization selection.

Tierney et al. (2018) addressed the question of the sensitivity of extratropical cyclones (ETCs) to changes in their environment, in order to assess how storms might change in future climates. The paper analyzed an ensemble of simulations of ETCs for varying environmental temperatures and baroclinicity, finding that storm strength increases with baroclinicity, but decreases with warming beyond a threshold temperature. The paper identifies convection as key to determining the response of storms to changes in their environment. The simulations suggest that ETCs will not uniformly strengthen with increasing temperature, but rather that convection will become more prevalent as temperature warms, and this will eventually cause a storm's maximum intensity to be lower than storms in lower temperature environments.

Ocean Modeling and Atmosphere/Ocean Coupling Advances:
Coupling of atmospheric and ocean processes is critical to understand the Earth's climate system, as is a deeper understanding of ocean mixing processes, which can strongly affect the impact of the ocean on the climate system. Canuto et al. (2018) present a mesoscale parameterization based on the solutions of the non-linear mesoscale dynamical equations. They found lowered transfer of mean potential energy to mesoscales in the parameterization, with steeper isopycnal slopes with deep-ocean stratification enhanced compared to previous parameterizations, precluding large unobserved heat uptake. The parameterization should eventually result in improved mixing in coupled atmosphere-ocean models. Mixing would of course influence ocean composition, including ocean carbon. Latto and Romanou (2018) undertook a regime analysis of the ocean carbon cycle by defining particular ocean carbon states both observations and models. The analysis showed the GISS model reproduces the cold and warm season regimes more skillfully in the North Atlantic than in the Southern Ocean and matches the observed seasonality better than the spatial distribution of the regimes. They found that model air–sea CO_2 flux biases in the North Atlantic stem from wind speed and salinity biases in the subpolar region and nutrient and wind speed biases in the subtropics and tropics. Nutrient biases are shown to be most important in the Southern Ocean flux bias.

Rind et al. (2018) showed that longer term global warming simulations with the GISS-E2-R climate model exhibited the occurrence of multicentennial shutdowns in North Atlantic Deep Water production despite a lack of freshwater input, such as one might expect from large amounts of Greenland ice sheet meltwater entering the ocean. These multicentury shutdowns were shown to be the direct result of cooling in the North Atlantic associated with an aerosol indirect effect in the model on cloud cover. Cooling was found to reduce evaporation within the North Atlantic, while warming outside of the NA region provided sufficient moisture to maintain precipitation. As global warming continues, warm temperature (low density) anomalies spread northward at depth in the North Atlantic eventually destabilizing the water column, even though precipitation input at the surface is initially unchanged. Internal ocean freshwater transports do not play an important role in creating these shutdowns, and the importance of the aerosol indirect effect in these runs is high because it strengthens sea surface temperature-evaporation feedback. While this may be relevant to the onset and end of the Younger Dryas, which occurred within a warming climate during the last deglaciation, the value to NASA is a better understanding of possible coupled atmosphere-ocean mechanisms influencing important large-scale ocean circulations.

Ocean biological systems are affected by mixing in addition to carbon, and are a topic of interest in modeling of the coupled climate system. Gregg et al. (2017) found that detecting trends in ocean chlorophyll with satellites is sensitive to data processing options and radiometric drift correction. However assimilating the data reduces sensitivity to algorithms and radiometry, as well as the addition of new sensors. This suggests the assimilation model has skill in detecting trends in global ocean colour. Using the assimilation model, spatial distributions of significant trends for the 18-year record (1998-2015) showed recent decadal changes, notably in the North and Equatorial Indian Oceans basins, which exhibit a striking decline in chlorophyll.

A strong test of our understanding of the coupled climate system is the capability to predict future states of various parts of it. Thus the significance of the Rousseaux and Gregg (2017) result which use a global ocean biogeochemical model combined with a forecast of physical oceanic and atmospheric variables from the NASA Global Modeling and Assimilation Office to assess the skill of a chlorophyll concentrations forecast in the Equatorial Pacific for the period 2012-2015 with a focus on the forecast of the onset of the 2015 El Niño event. The forecast was able to reproduce the phasing of the variability in chlorophyll concentration in the Equatorial Pacific, including the beginning of the 2015-2016 El Niño. Forecasts with a 3-month lead time were on average the closest to the observations, while the forecast with a 9-month lead time were the furthest These results indicate the potential for forecasting chlorophyll concentration and provides an initial basis for including the effects of El Niño events on fisheries and other ocean resources.

Land/Atmosphere Coupling

Understanding and appropriately representing in models the coupling between land and atmospheric processes remains an active area of research in the CVC portfolio. Progress was made this year in understanding general model representativeness errors in Land-Atmosphere coupling in Dirmeyer et al. (2017). The paper established that models underrepresent the feedback of surface fluxes on boundary layer properties and may overrepresent the connection between soil moisture and surface fluxes. Models also underrepresent spatial and temporal variability relative to observations, leading to difficulty in the partitioning of surface energy. The study provides goals for the future development of coupled land–atmosphere models.

In terms of understanding the effect of representation of Land/Atmosphere coupling on climate predictions, Broxton et al. (2018) found significant effects on subseasonal-to-seasonal prediction from initialization of snowpack. The paper finds that snowpack initialization uncertainties affects the seasonal forecasts of different variables like surface temperature in Apr-Jun more strongly than do sea surface temperature uncertainties, whose influence is mostly felt on the edges of continents. This is because SST initialization uncertainty is relatively small, translating into small impacts on seasonal forecasting. Thus, improvements in forecasting would benefit from more accurate measurements and initialization of snowpack based on satellite remote sensing.

Cryospheric Modeling

Near surface air temperatures can substantially influence the cryosphere, so proper representation of near surface temperatures in models and in data assimilation systems is important. This year, Eyre and Zeng (2017) evaluated five surface air temperature data sets, including that of the NASA "MERRA-2" reanalysis. The paper found that the MERRA-2 reanalysis performed better than the other data sets, with a mean absolute error less than 2 degrees Celsius in all months. It also showed that this bias is much lower than the 31 Earth system model runs from the CMIP5 archive, which reach approximately 5 degrees Celsius for the 1901 – 2000 average bias. This shows the value of data assimilation for providing comprehensive, observation-constrained estimates of important cryospheric properties. Another concern governing the cryosphere is its melting, and more specifically how rapidly that ice is melting and what effects it might have on sea level rise along the Earth's coastlines. Larour et al. (2017) addressed this question for coastal locations by using an adjoint model to identify to what location on the Greenland ice sheet local sea level changes are most sensitive. This enables the prediction of the effects of Greenland ice sheet melting at coastal locations worldwide.

Chemistry/Climate Modeling

Representation of chemistry and chemical processes in global climate models continued to advance in 2017. The representation of chemical processes in the GEOS-5 Modeling system now allows the user a number of choices regarding chemical mechanisms and emissions parameterization, and the extent to which the chemical processes are integrated (for instance, radiatively) with the overall GEOS modeling system The capability of choosing mechanism is based on the utilization of the Earth System Modeling Framework (ESMF) infrastructure, as described in Nielsen et al., (2017). One topic of investigation is the effect of running the model interactively, where chemical processes interact with other processes, for instance the circulation, or running the model with a fixed dynamics, corresponding (say) to a particular time. Yu et al. (2018) find that there is a significant loss of vertical transport in the fixed circulation ("off-line") mode, due to missing transient grid-resolved convection and grid coarsening. They also find that off line averaging of mixing depths must give more weight to deeper values to properly represent boundary layer mixing. However, using the fixed circulation model version, Strahan and Douglass (2018) showed that ozone depletion in the Antarctic polar vortex is declining, and that this decline is a response to a decline in stratospheric chlorine levels. The relationship between chemical processes and climate fluctuations was addressed in Albers et al. (2017), with a finding that the strength of the association between ENSO and NAM influence stratosphere-to-troposphere ozone transport. In particular, the overall strength of the winter stratospheric NASM is a useful predictor of the strength of stratospheric ozone intrusions into the troposphere.

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FY 2018 Annual Performance Indicator	FY 15	FY16	FY17	FY18
ES-18-9: 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.	Green	Green	Green	Green

Annual Performance Indicator ES-18-11: Demonstrate planned progress in characterizing the dynamics of Earth's surface and interior, improving the capability to assess and respond to natural hazards and extreme events.

NASA's Earth Surface and Interior focus area (ESI, 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 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* (Davis et al., 2016, http://go.nasa.gov/2hmZLQO). The ESI chapter will identify how this year's highlights respond to addressing these *CORE* challenges, denoted by seven shorthand tags throughout. Accomplishments demonstrate continued interest in and developments related to anthropogenic perturbations and signals [1. Plate boundaries, 2. Tectonics and surface processes, 7. Human impact], leading research in geomorphic processes [2. Tectonics and surface processes] and vertical land motion [3. Solid Earth and sea level], advancing capabilities and understanding of the Earth system through new airborne campaigns [4. Magmatic systems], novel new insights from geodetic and geopotential field observations into the deep Earth [5. Deep Earth, 6. Magnetic field], advancements in geodetic imaging and ground networks, and other highlights described below.

Lithospheric Processes

Lithospheric structure and dynamics, and interactions between these processes and the oceans, hydrologic system, and atmosphere are critical to understanding the Earth system. This includes the motion and rotation of tectonic plates, the mechanisms that drive volcanic/magmatic processes, elastic properties of the crust and mantle, and the effects of surface loading resulting from surface water, ground water, other fluids, glaciers, and ice sheets. Signals related to natural and anthropogenic perturbations to the Earth system, from the water cycle to energy production settings, continues to be a growing area of study that is advancing our understanding coupled Earth systems. ESI has also seen a renewed interest in and sought to foster studies of surface processes, particularly those driving topographic change. All of these studies also represent enabling research for the hazards advancements described in a subsequent section. Below are highlights of ESI Focus Area funded research accomplishments that have matured in FY2018 and represent research that has been funded over the past several ROSES cycles.

Tectonics and Earthquake Geophysics

There has been significant progress on understanding the nature of plate boundary deformation, particularly in space geodetic identification of the existence of new distinct plates and microplates, their relative motion, and their motion with respect to the no-net-rotation global frame. Given that the exact processes that drive tectonic plates are still not fully understood, ESI supports innovative research in advancing our understanding of tectonics and earthquake processes. Transient deformation has emerged as a research focus for improving the understanding of fault zone constituent properties and forcing mechanisms. The three publications described below highlight exciting new research into earthquake transients.

Fault creep accounts for the release of up to half of the seismic moment budget throughout the earthquake cycle and contribute to the degree to which a fault is locked, the frequency and magnitude of earthquakes, and the triggering of nearby earthquakes. Khoshmanesh and Shirzaei (2018: *Nature Geoscience*) investigate surface deformation measured by radar interferometry along the central San Andreas Fault between 2003 and 2010 to constrain the temporal evolution of creep and find that that slow-slip events are ensembles of localized creep bursts that aseismically rupture isolated fault compartments. Using a rate-and-state friction model, they show that effective normal stress is temporally variable on the fault, and support this using seismic observations and propose that compaction-driven elevated pore fluid pressure in the hydraulically isolated fault zone and subsequent frictional dilation cause the observed slow-slip episodes. Their analysis of the 2004 M_w 6 Parkfield earthquake suggest that it might have been triggered by a slow-slip event, which increased the Coulomb failure stress by up to 0.45 bar per year. This implies that while creeping segments are suggested to act as seismic rupture barriers, slow-slip events on these zones might promote seismicity on adjacent locked segments. These findings advance our understanding of *CORE* challenges [1. Plate boundaries] and [2. Tectonics and surface processes].

Over the past decade, geodetically detected slow slip events (SSEs) and accompanying nonvolcanic tremor have been observed in many subduction zones, expanding the spectrum of known fault behaviors and providing insight into fault mechanics. Although they do not release strain at the same rate as normal earthquakes, fault slip during SSEs are typically associated with shear failure on the plate interface, therefore characterizing near-trench behavior of subduction megathrust faults is critical for understanding earthquake hazard and tsunami generation. Jiang *et al.* (2017: *Geophysical Research Letter*) combined measurements from seafloor pressure sensors near the trench and an onshore GPS network in a time-dependent inversion to image the initiation and migration of a well-documented slow slip event (SSE) in 2007 at the Nicoya Peninsula, Costa Rica. They found that this shallow SSE initiated on the shallow subduction interface at a depth of ~15 km, where pore fluid pressure is inferred to be high, and propagated all the way to the trench. This migrating event may have triggered a second subevent that occurred 1 month later. Their findings document the release of elastic strain at the shallow part of the subduction megathrust and suggest prior accumulation of elastic strain. When viewed in conjunction with other near-trench shallow slow slip investigations, their results suggest that near-trench strain accumulation and release at the shallower portions of the subduction interface is more common than previously thought. These findings advance our understanding of *CORE* challenges [1. Plate boundaries] and [2. Tectonics and surface processes].

There is increasing interest in the understanding the influence of nontectonic transients on seismicity and their possible role in earthquake triggering. Kraner *et al.* (2018: *J. Geophys. Res.: Solid Earth*) analyzed continuous GPS data (2007-2014) of in Northern California and detected a seasonal positive dilatational strain and Coulomb stress transient in the South Napa region peaking just before the 24 August 2014 M6.0 South Napa earthquake, which corresponds to 3-mm of horizontal expansion of the Earth's crust encompassing South Napa and the northern San Pablo Bay Peaks. These transients reverse sign in the winter to contraction. The dilatational transient Coulomb stress changes were about a factor of two higher in the epicentral region. By analyzing the previous 8 years of GPS data, they found that a similar pattern of crustal motion repeats every summer and have determined that this crustal expansion releases pressure on nearby faults, including those in the West Napa fault system, making them more likely to slip during the summer months. Large seasonal variability in the amount of groundwater in the Sonoma and Napa Valley subbasins may contribute to the observed changes. This manuscript contributed to multiple *CORE* challenges [1. Plate boundaries, 2. Tectonics and surface processes, and 7. Human impact].

Magmatic processes

ESI's volcanic process objectives are to: Identify and characterize Earth's active magmatic systems globally; Assess hazards of active and potentially active volcanoes; Improve the capability to forecast the start and end of an eruption; Understand the relationships between surface deformation, seismicity, thermal emissions, changes in gravity, emissions of gasses, and eruptions; Improve the capability to forecast quantities and types of eruptive products and their distribution in space and time with application to the wide range of volcanic hazards; Investigate interactions among magmatic systems, earthquakes, and tectonics, and; Improve our understanding of the overall impact of volcanoes and their eruptions on the Earth system. The publications below focus on *CORE* challenge [4. Magmatic systems], with additional contributions to [1. Plate boundaries, 2. Tectonics and surface processes, and 5. Deep Earth].

Recent studies have widely improved our understanding of how volcanoes respond to tectonic and climatic forcing, yet, little is still known about how volcanoes interact and whether neighboring volcanoes represent individual separated plumbing systems or the surface expression of a large connected magmatic system at depth. Brothelande *et al.* (2018: *Scientific Reports*) used GPS time-series and deformation modeling to show how Aira caldera and Kirishima, two adjacent volcanic centers in Kagoshima graben (southern Japan), interacted during Kirishima unrest in 2011. Whereas Aira caldera had been inflating steadily for two decades, it deflated during the eruption of Kirishima which started with a large-volume lava extrusion. This deflation, which cannot be explained by stress changes, is interpreted as the result of magma withdrawal from the Aira system during the Kirishima replenishment phase. This study highlights the behavior of connected neighboring volcanic systems before and after a large eruption, and the importance of taking into account volcano interactions in eruption probability models.

Copahue volcano straddling the edge of the Agrio-Caviahue caldera along the Chile-Argentina border in the southern Andes has been in unrest since inflation began in late 2011. Its asymmetric deformation pattern extending into the caldera observed by radar interferometry suggests a complex magma plumbing system. Lundgren *et al.* (2017: *J. Geophys. Res.: Solid Earth*) constrained models of its plumbing system with satellite and airborne (UAVSAR) InSAR surface displacement observations. Displacement time series from RADARSAT-2 and COSMO-SkyMed satellite data span the entire inflation period from 2011 to 2016, with their initially high rates of 12 and 15 cm/yr, respectively, slowing only slightly through 2016. InSAR observations for the 2013–2016 time period constrained a two-source compound dislocation model, with a rate of volume increase of 13 x $10^6 m^3$/yr. They consisted of a shallow, near-vertical, elongated source centered at 2.5 km beneath the summit, and a deeper, shallowly plunging source centered at 7 km depth connecting the shallow source to the deeper caldera. The deeper source is located directly beneath the volcano tectonic seismicity with the lower bounds of the seismicity parallel to the plunge of the deep source. This suggests a deep conduit or transfer zone where magma moves from the central caldera to Copahue's upper edifice.

Constraining lava discharge rate is important to understand the dynamics of effusive eruptions, characterizing the magmatic source at depth, and is a critical input parameter for most lava flow modeling including estimating the duration of the eruptive episode. Bonny *et al*. (2018: *J. Geophys. Res.: Solid Earth)* compared discharge rates estimated using data from MODIS satellite imagery with estimates of discharge rates derived from comparing intermittent ground-based measurements of flow field volume. The time-averaged discharge rates reveal a pulsed increase in the first few days of the eruption. Although the trends of the satellite- and ground-based discharge rates are similar, the ground-based estimates are systematically higher than the satellite-derived estimates (about 2 to 3 times higher) in the first 30 days of the eruption, and relatively close (within 30%) for the next 20 days. Conversely, during the final 130 days, the satellite-based estimates are systematically higher than the ground-based estimates (about 2x higher). This difference likely arises from the assumption of the lava flow surface temperature used in the space-based calculation, which may not be entirely representative of this uniquely large and intense basaltic eruption. However, the satellite-based technique yields a total erupted volume of about 1.21 km^3 in good agreement with the 1.2 km^3 derived from field observations and mapping.

Coupled Solid Earth-Hydrologic-Anthropogenic Processes

Advances of space geodesy over the past decade have enabled transformative research progress in the rapidly evolving field of hydrogeodesy. As geodetic techniques advance in capability, i.e. sensitivity and resolution (spatial and temporal), the contributions of water (atmospheric, surface, ground, soil, organic, frozen) and water phase (gas, liquid, solid) become increasingly larger components measured in the geodetic signal. Six of the seven science challenges identified in the CORE Report either directly address water as a signal source or need to mitigate the effect of water in the geodetic time-series to advance our understanding of the science. The hydrogeodesy research that matured during the FY18 GPRA cycle underscores the how widespread and pervasive that natural and anthropogenic movement of water influence geodetic time-series, including a cluster of publications on the recent California droughts.

Drought struck California during 7 of the 9 years from 2007 to 2015, reducing the state's available water resources with pumping groundwater in the Central Valley produced widespread land subsidence. Uplift of the adjacent Sierra Nevada mountains has been proposed to be either tectonic uplift or solid Earth's elastic response to unloading of Central Valley groundwater. Argus *et al.* (2017: *J. Geophys. Res.: Solid Earth*) inverted GPS vertical displacements recording solid Earth's elastic response to infer changes in water storage across the western U.S. from January 2006 to October 2017. They found that of the 24 mm of uplift of the Sierra Nevada from October 2011 to October 2015, just 5 mm is produced by Central Valley groundwater loss, less than 2 mm is tectonic uplift, and 17mm is solid Earth's elastic response to water loss in the Sierra Nevada. They track 10s of km^3 of water volume gain and loss throughout the study, including the loss of 45 ± 21 km^3 of water during severe drought from Oct. 2011-2015 (95% confidence limits). They inferred that there must be large loss of either deep soil moisture or groundwater in river alluvium and in crystalline basement in the Sierra Nevada.

Chaussard *et al.* (2017: *J. Geophys. Res.: Solid Earth*) combined InSAR (COSMO-SkyMed) and GPS data to track surface elevation response during the recent droughts in managed Santa Clara Valley aquifer in Northern California. Their analysis found subsidence associated with water withdrawals, but thanks to intensive groundwater management efforts, the basin started to rebound in late 2014 even though the drought deepened. By 2017, water levels were back to their predrought levels, while elevations had not yet fully rebounded due to the delayed poroelastic response of aquitards and their large elastic compressibility. Similarly, Ojha *et al.* (2018: *Water Resources Research*) used InSAR in the California's Central Valley to investigate the depletion and degradation of the aquifer-system during 2007–2010, when the entire valley in a severe drought. They found that ~2% of total aquifer-system storage was permanently lost with the irreversible inelastic compaction of the aquifer system. Over this period, the seasonal groundwater storage change amplitude of 10.11 ± 2.5 km^3 modulates a long-term groundwater storage decline of 21.32 ± 7.2 km^3.

Systematic satellite InSAR imagery collection strategies are making it possible to have sufficient data to generate adequately dense time-series with sufficient spatial coverage to begin to detect and characterize the full extent of anthropogenic activity on the Earth's surface related to the extraction and injection of water and hydrocarbons. Semple *et al.* (2017: *Remote Sensing*) analyzed more than 5,000 interferograms from data available at the ASF and the WInSAR archives for ERS, Envisat, and ALOS satellites, collectively spanning the period 1992–2015. This compilation, while neither complete in terms of spatial and temporal coverage nor uniform in quality over the North America, contains 263 different areas of likely anthropogenic ground deformation, including 65 that were previously unreported. The sources can be attributed to groundwater extraction (50%), geothermal sites (6%), hydrocarbon production (20%), mining (21%), and other sources (3%) such as lake level changes driven by human activities and tunneling. A number of other investigations focused on specific addressing specified area with anthropogenic activity. Bekaert *et al.* (2017: *Scientific Reports*) combined GPS with InSAR to assess subsidence in Hampton Roads, VA. Even though this area is technically challenging to use InSAR with extensive vegetation, they successfully characterized spatially variable subsidence in their study area. In the Western US, tectonic deformation signals can be overprinted by anthropogenic activity, such as hydrocarbon production or geothermal production. Xu *at al.* (2017: *IEEE Transactions on Geoscience and Remote Sensing*) develop new algorithms to process and analyze Sentinel-1 data for the Cerro Prieto geothermal field in Northern Baja California, Mexico. The geothermal field is the second largest in the world and poses a challenging InSAR target because of extensive agriculture production and challenging atmospheric conditions. Their analysis found 160 mm/yr of subsidence associated with the extraction of geothermal fluids and heat, and ~40 mm/yr of tectonic deformation across the proximal ends of the Imperial, Cerro Prieto, and Indiviso faults.

Vertical Land Motion and Relative Sea Level

The CORE Reports science challenge 3 is, "How does the solid Earth respond to climate-driven exchange of water among Earth systems and what are the implications for sea-level change?" Understanding the transport of water on seasonal time scales over the entire surface of Earth has only been possible during the past decade and a half where the GRACE mission has provided scientists with the first maps of global transport of surface water mass and, simultaneously, of the slow movements of the solid rock interior associated with glacial isostatic adjustment (GIA). Geodetic techniques (*i.e*. InSAR, GPS, and lidar) are characterizing both localized and regional natural and anthropogenic subsidence/uplift, thereby enabling improved models of absolute sea level rise. The following two publications focus on a few *CORE* challenges [1. Tectonics and surface processes, 3. Solid Earth and sea level, and 7. Human impact].

Coastal flooding is likely to be the biggest socioeconomic impact of sea level rise (SLR) in the 21st century. Several U.S. states (including Texas, Louisiana, and Florida, as well as U.S. territories such as Puerto Rico and the Virgin Islands) have just experienced devastation caused by the unprecedented flooding after Hurricanes Harvey, Irma, and Maria. Storm intensity, associated rainfall, and storm surges affecting the coastal area were likely amplified by the elevated ocean temperature caused by ongoing global climate change. Although the contribution of these sources to SLR is fairly well understood, the rate of relative SLR (RSLR) can vary significantly due to a number of other processes such as isostatic adjustments, ocean currents, earthquakes, and volcanic episodes, as well as local land subsidence (LLS) associated with sediment and aquifer-system compaction. Shirzaei and Bürgmann (2018: *Science Advances*) used synthetic aperture radar interferometric measurements and global navigation satellite system data to show subsidence rates of less than 2 mm/year along most of the coastal areas along San Francisco Bay. However, they found that rates exceed 10 mm/year in some areas underlain by compacting artificial landfill and Holocene mud deposits. They develop maps that estimate 100-year inundation hazards solely based on the projection of sea level rise from various emission scenarios underestimate the area at risk of flooding by 3.7 to 90.9%, compared with revised maps that account for the contribution of local land subsidence. Given ongoing land subsidence, they projected that an area of 125 to 429

km^2 will be vulnerable to inundation, where the minimum area is 2.45 times larger than considering sea level rise alone.

Karegar *et al.* (2017: *Scientific Reports*) integrated GPS and GRACE data to assess the frequency and location of nuisance flooding along the eastern seaboard of North America. Their results show that vertical land motion induced by recent anthropogenic activity and glacial isostatic adjustment are contributing factors for increased nuisance flooding. Their results have implications for flood susceptibility, forecasting and mitigation, including management of groundwater extraction from coastal aquifers.

Dynamic Surface Topography and Geomorphology
Topography of the land and seafloor is being imaged at increasing resolution from spaceborne, airborne, and ground-based sensors, making ubiquitous high-resolution topographic datasets possible, but with variable spatial coverage. Accurate topographic datasets not only underpin many remote sensing techniques, they enable sub-pixel georegistration and analysis of diverse datasets, correct for imagery specific and elevational dependent artifacts, and provide a common datum supporting sciences that span ESD's Focus Areas and Applied Science Programs. The last two decades have seen an explosion in the technology, methodologies, (*i.e.* IfSAR, lidar, structure-from-motion), and platforms (ground, mobile, UAS, aircraft, satellite) to collect ever increasingly dense 3D and 4D elevation datasets at finer scales where processes of interest operate and important transitions and phenomena occur (*e.g.*, hillslope–fluvial transition and surface-rupturing earthquake displacements). ESI has a long history of supporting new and innovative topographic technologies and scientific research, including the SRTM which remains the most widely used global DEM. Static and dynamic topographic data are fundamental to supporting research spanning ESI's portfolio.

Garvin *et al.* (2018: *Geophysical Research Letters*) received extensive media interest and graced the cover image for GRL. This quantitative geomorphic study used high-resolution (~50 cm) topography datasets derived from high-resolution satellite imagery to track erosional process associated with a new formed island in the southwestern Pacific unofficially named Hunga Tonga Hunga Ha'apai (HTHH), which was not expected to persist above the tideline for more than a few months. Their analysis found that HTHH had an erosion rate of ~0.00256 km^3/year, which suggests a lifetime of ~19 years (potentially up to 42 years) if the rates remain unchanged. The HTHH is disappearing much faster than Surtsey, but far slower than recent nearby activity indicates. Regional submarine topography shows that shallow-water topology may be an important factor in explaining the unanticipated lifetime of this new island, together with internal strengthening by hydrothermal mineralization. The stages of erosion at the HTHH island may have implications for similar landforms discovered on Mars and their evolution in association with surface water levels. This manuscript contributed to *CORE* Challenges [2. Tectonics and surface processes] and [4. Magmatic systems], as well as supported *CORE* Observational Strategies.

Natural Hazards Research

New and innovative natural hazards research and analysis is providing insights into earthquake, landslide, debris flow, volcanic, and sinkhole processes, along with new geodetic analysis approaches for advancing scientific understanding and hazard early warning capabilities. 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 and IDS-supported publications that contributed to our understanding of Natural Hazards during this year.

Mass Flows

The three-dimensional (3D) geometry and movement of landslides, particularly large landslides, can be complex and difficult to characterize. Conventional stability analyses require estimates of depth to the basal slip surface and material properties, which are usually obtained from field investigations at a few specific locations. Hu *et al.* (2018: *Geophysical Research Letters*) combined GPS and InSAR in a new approach on a ~4 km^2 reactivated translational landslide in the Columbia River Gorge (Washington State), which moves mainly during the winter rainy season. Results reveal the complex three-dimensional shape of the landslide mass, how onset of sliding relates to cumulative rainfall, how surface velocity during sliding varies with location on the topographically complex landslide surface, and how the ground surface subsides slightly in weeks prior to downslope sliding.

Fast-moving, highly destructive debris flows triggered by intense rainfall are one of the most dangerous post-fire hazards, but assessing debris flows with remote sensing has been challenging. Donnellan *et al.* (2018: *Earth and Space Science*) used UAVSAR data spanning the 2017 Thomas fire in southern California and developed an innovative approach to analyze UAVSAR high-resolution L-band SAR data both polarimetric and interferometric imagery to map the fire extent and then characterize debris flow paths. Their results are also compared nicely with imagery from Planet Labs Dove satellites. This study shows the potential to track debris flows with SAR.

Anthropogenic Hazards

Human activities such as those associated with hydrocarbon production including fluid injection, fracking, and hydrocarbon extraction have resulted in surface instability, leading to geohazards such as surface heave/subsidence, fault reactivation, induced seismicity, and sinkhole formation. Locating, characterizing, and modeling this classification of geohazard has both scientific and societal value. Kim and Lu (2018: *Scientific Reports*) used Sentinel-1 SAR data in West Texas to probe the causal mechanisms of ground deformation, encompassing oil/gas production activities and subsurface geological characteristics. Their analyses determined that human activities, the injection of fluids (saltwater, CO2) to stimulate hydrocarbon production, salt dissolution in abandoned oil facilities, and hydrocarbon extraction each have had negative impacts on the ground surface (uplift and subsidence), damaged infrastructure, and induced seismicity.

Volcanic Hazards

The ability to understand/forecast/predict both when a volcano is going to erupt and when ultimately when an eruption will cease are desired capabilities from both a science and a societal perspective. The following two manuscripts advanced our understanding bracketing eruptions. Rivera et al. (2017: *Geophys. Res. Lett*) combined COSMO-SkyMed interferograms with GPS data at the onset of unrest at Cotopaxi volcano in Ecuador beginning in April 2015 and found evidence of precursory deformation, with a maximum uplift on the western flank of 3.4 cm from April to August 2015. Deformation could be explained by an inclined sheet intrusion located a few km southwest of the summit with an opening volume of 6.8×10^6 m^3, extending from a depth of 12.1 km and shallowing to 5.5 km below the summit, that contributed to internal edifice growth. The temporal coincidence of deformation prior to the eruptions potentially suggests that short-term eruptions at Cotopaxi are partly controlled by episodic edifice growth. While the volcanological community has focused much attention on predicting when an eruption will begin, mainly taking cues from seismicity, ground deformation, thermal or gas emissions, there has been less attention has been given to accurately forecasting when an eruption will end. Bonny and Wright (2017: *Bull Volcanology*) used thermal infrared remote-sensing data acquired by MODIS to derive time-averaged discharge rate time series using existing algorithms for 104 eruptions at 34 volcanoes over the last 15 years. They found that 32 eruptions followed the pattern predicted by Wadge (1981). Based on the MODIS-derived maximum lava discharge rate and a decay constant that best fits the exponential waning phase, the time at which the discharge equals zero, and thus the point at which effusion ends can be predicted. The accuracy of the prediction improves with the number of data points so that, in the ideal case, the end of effusion can be retro-casted before half of the eruption duration has passed.

Volcanology Airborne Campaigns

In support of advancing our understanding of magmatic systems and volcanic hazards research, ESI had a leading roles in two 2018 airborne campaigns.

ESI participated in coordination, support, and implementation of year two of the HyspIRI Hawaii Preparatory Airborne Campaign, which flew on the NASA ER-2 January-February 2018. The investigations included five ROSES research projects studying volcanic emissions and eruptive activity. This year the Hyperspectral Thermal Emission Spectrometer (HyTES, https://hytes.jpl.nasa.gov) was included as part of the ER-2 payload. Preliminary analyses of the data collected demonstrate for the first time that HyTES is able to resolve volcanic SO_2 emissions. HyTES is expected to help inform the optimum band positions for future Surface Biology and Geology observations by satellite.

ESI also coordinated and supported the GLISTIN-A rapid response campaign for radar imaging of deformation and lava effusion associated with the May 2018 eruption of Kilauea volcano. The Big Island was previously surveyed by GLISTIN-A in 2017, providing a base map. Six repeat flights during May-June 2018 provided data for difference DEMs that were generated to measure topographic changes related to the eruption. Researchers are presently evaluating the use of these Ka-band repeat observations for the estimation of lava erupted volume with time, which will in turn be used to constrain models of volcano plumbing systems.

Deep-Earth Processes

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

Probing Mantle Rheology High and Low
Earth's elastic and density structure largely vary with depth. However, beginning in the early 1980s, images of Earth's interior provided by seismic tomography have revealed more complicated features characterized by laterally varying perturbations in seismic wave speed. These anomalies reflect thermal and/or compositional heterogeneity linked to mantle convection, the main driving force for plate tectonics. Constraining the thermochemical structure of Earth's mantle, and its associated dynamics, remains a key goal in global geophysical research. In a paper published in Nature, Lau *et al.* (2017, *Nature*) advanced a novel method called tidal tomography to probe the rheology of the deep mantle and provide new bounds on its heterogeneities. Tidal tomography uses GPS-based measurements of semi-diurnal body tide deformation to invert for mantle properties at depth. The authors found that the mean density of two large lower-mantle anomalies is about 0.5 per cent higher than the average mantle density across the same depth range. They propose that the buoyancy of these structures is dominated by the enrichment of high-density chemical components, probably related to subducted oceanic plates or primordial material associated with Earth's formation. This is a seminal contribution to address *CORE* challenge [5. Deep Earth].

Kreemer *et al.* (2018, *J. Geophys. Res.: Solid Earth*) used more than 3000 GPS station velocities to image 3D deformation due to glacial isostatic adjustment across North America in a study that addresses *CORE* [3. Solid Earth and sea level] and [5. Deep Earth]. They found that most of the plate is moving at 1–2 mm/year horizontally towards central Canada. Consequently, around most of Canada there is a zone where the crust is contracting. Within Canada, the crust is extending outward and is moving upward rapidly. These patterns can be explained by the process of the crust and mantle still rebounding from the melting of the Laurentide ice sheet. The fact that this causes the land to move towards the former ice sheet is an unexpected result that will be useful in understanding the viscosity structure of the upper mantle.

Heat Transport in the Earth's Interior

Mantle plumes are upwelling instabilities within the mantle driven by thermal and/or composition buoyancy, possibly from the core-mantle boundary. As a plume rises and impinges on the base of the lithosphere, carries anomalous heat that is manifest in increased geothermal heat flux at the surface. What happens when a plume rises beneath an ice-covered continent? Seroussi *et al.* (2017, *J. Geophys. Res. Solid Earth*) addressed the question of the influence of a mantle plume on ice sheet basal conditions in West Antarctica. Building on recent seismic images that support the plume hypothesis as the cause of Marie Byrd Land (MBL) volcanism and geophysical structure, they used numerical experiments to characterize the impact of the plume on geothermal heat flux and ice sheet basal conditions. In order to be consistent with observations of basal hydrology in MBL, the authors suggest an upper bound on the plume-derived geothermal heat flux of 150 mW/m^2. They found that such a mantle plume would have an important local impact on the ice sheet, with basal melting rates reaching several centimeters per year directly above the hotspot. This study also spans *CORE* [3. Solid Earth and sea level] and [5. Deep Earth].

Core-Mantle Coupling and Earth Rotation

The solid Earth's rotation axis orientation and rotation rate changes on various timescales. Apart from lunar and solar tidal interactions, these variations are due to angular momentum exchanges between the solid Earth and other components of the Earth system. Relative angular velocity changes and the mass redistribution within the Earth system both play a role by exerting torques on the solid Earth under the conservation of the total angular momentum. As a result, observed changes in the Earth's rotation have long been used to understand the dynamic processes in the Earth. Kuang *et al.* (2017, *J. Geophys. Res.: Solid Earth*) investigated electromagnetic coupling across the core-mantle boundary as a potential mechanism driving decadal polar motion using numerical geodynamo simulations. They explored a range of different geodynamo parameters (Rayleigh numbers and magnetic Rossby numbers) and found that electromagnetic core-mantle coupling could explain a substantial portion, if not all, of the observed decadal polar motion over several decadal periods with amplitudes larger than 5×10^{-8}, or approximately 10 milliseconds of arc. In particular, they found that the predicted 60-year polar motion deserves special attention for future observations and studies of polar motion due to core-mantle coupling. This study strongly couples across two *CORE* challenges [5. Deep Earth, 6. Magnetic field].

New Swarm Level-2 Product: Oceanic M_2 Tidal Magnetic Field From NASA/GSFC/DTU

As conductive sea water moves through Earth's ambient magnetic field it generates secondary magnetic fields through a process known as motional-induction. This is true for tidal motions also, of which the principal lunar semi-diurnal tide, M_2, is the largest on a global scale. An analysis of CHAMP data using the "Comprehensive Inversion" (CI) technique, developed by NASA/GSFC and the Danish Technical Institute (DTU), and culminating in the "Comprehensive Model 5" (CM5) model was previously successfully used to extract the M_2 field. The CI approach was then applied to the first 20 months of the ESA Swarm magnetic constellation mission data and successfully extract M_2 again.

The CI method considers and co-estimates all the major near-Earth magnetic field sources in order to obtain optimal separation of the signals. It provides one of two chains of magnetic field Swarm Level-2 (L2) products that originally included fields describing the core, lithosphere, ionosphere, magnetosphere and associated induced sources. The M_2 extraction was originally a by-product of the CI procedure, but has since been deemed so impressive that it is has now been added as an official ESA Swarm L2 product in 2018 in a notable contribution to advancing This is a seminal contribution to address *CORE* challenge [6. Magnetic field]. Furthermore, all L2 magnetic field products have two versions derived from at least two different methods, but since the NASA/GSFC CI method is the only one capable of producing an M_2 at the desired quality, there is only one version of this product available.

Geodetic Imaging

Synthetic aperture radar (SAR) and interferometric SAR (InSAR) data are critical to enabling many ESI research objectives focused on surface deformation. Significant contributions continued to flow from UAVSAR, and progress continued towards realizing the NASA-ISRO Synthetic Aperture Radar (NISAR) satellite mission.

NASA-ISRO Synthetic Aperture Radar (NISAR) Mission

NISAR (https://nisar.jpl.nasa.gov/) has been in Phase C since August 2016. The project has made steady on-plan progress toward the Project Critical Design Review (CDR), to be held in October 2018. Leading up to this CDR, the Project has conducted a thorough set of system-level and subsystem-level CDRs, including the L-band Instrument CDR, and the Science pre-CDR peer review, all of which were evaluated very highly.

The science team worked with the project science and mission team to develop a comprehensive "Science Users' Handbook" which is now available on the NISAR website at https://nisar.jpl.nasa.gov/files/nisar/NISAR_Science_Users_Handbook.pdf. This document describes everything about the mission that a science or applications user would need to know, including the science, observation plan, radar modes and performance characteristics, product descriptions, and some technical tutorial background for beginners. This document will be update periodically as the mission characteristics evolve.

The solid-Earth team led the way in developing a joint science plan with ISRO, and in the past year, they have augmented the plan considerably. The plan now consists of a three-pronged approach, including a) workshops that foster greater collaboration between the US and Indian geodetic and geophysical communities, the first of which is scheduled for November 2018; b) studies that focus on geodetic science, including mitigating errors, cal/val using geodetic networks, and product exchanges to test compatibility; c) studies that focus on geophysical science, interseismic coupling in the Himalayas, co- and post-seismic studies of the Bhuj earthquake, land subsidence, landslides, and volcano deformation studies.

In support of these activities, there were a range of team meetings. In March 2018, a Science focused technical meeting (FTM) was held in in Ahmedabad, India. At the FTM, NASA and ISRO scientists continued the discussions on scientific and geographic areas of common interest and refined joint science plans in development, cal/val, and notably prepared for ISRO's participation in the pre-CDR Science Review. There were NISAR science team meetings held at the University of Massachussettes, Amherst, in October 2017 and at the University of Miami in February 2018.

The applications subgroup finalized the 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. The 21 white papers they produced over the past several years, available on the NISAR website, have been used extensively to explain to the public and government stakeholders the potentials for NISAR data utilization.

The solid-Earth subgroup continued to press the project for a re-evaluation of the overall left-looking/right-looking strategy for the observing both poles. Since 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 Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) Facility
JPL was tasked by NASA to operate the P-band (AirMOSS) and Ka-band (GLISTIN-A) radars as facility instruments together with UAVSAR's L-band radar beginning in October 2017 (https://uavsar.jpl.nasa.gov/). The UAVSAR team has been building up instrument spares with the goal of operating two instruments simultaneously in support of science campaigns. The team has also developed a new solid-state recording subsystem with commercial components to replace the existing recording subsystem that has become obsolete.

During the one-year time period from June 15, 2017 to June 14, 2018, UAVSAR conducted 81 science/engineering flights totaling 402 flight hours. Amongst all three instruments (L-, P-, and Ka-band), 800 flight lines were acquired over the United States, Canada, and Greenland. The project supported 11 Principal Investigators performing research on 7 science disciplines, as well as rapid response efforts and technology development. These ongoing flights include targets supporting research on Sacramento

Delta subsidence, San Andreas Fault processes, and landslide processes in Colorado and Northern California. ESI also coordinated and supported the GLISTIN-A rapid response campaign for radar imaging of deformation and lava effusion associated with the May 2018 eruption of Kilauea volcano, as described in the Natural Hazards Research section above.

On the processing front, repeat-pass InSAR processing capability has been added to the P-band radar to facilitate deformation studies that require longer wavelength radar, such as permafrost thawing. The Ka-band processor's calibration capability has also been greatly improved to produce DEMs with meter level height accuracy and bias without ground control points.

Overall science results based on UAVSAR data were published in 30 refereed journal papers, covering topics in solid-Earth science, applied science, cryosphere, hydrology, land cover/land use change, space archaeology, and terrestrial ecology. Publications are continuously updated on the UAVSAR website at http://uavsar.jpl.nasa.gov/cgi-bin/publications.pl.

InSAR Enabling Research

InSAR processing methods are critical to many avenues of ESI science, while also providing high-resolution maps of surface deformation applicable to many scientific, engineering, and management studies. Despite its utility, the specialized skills and computer resources required for InSAR analysis remain as barriers for truly widespread use of the technique. Zebker (2017: *IEEE Geoscience and Remote Sensing Letters*) presented an approach for delivering radar data products to users that are ready to use in more natural coordinates, without requiring further processing, and in as small volume as possible. Such approaches have the potential to grow the InSAR user community.

Liang *et al.* (2018: *IEEE Transactions on Geoscience and Remote Sensing*) conducted InSAR time series analysis of ALOS-2 ScanSAR data, analyzing and when possible correcting error sources. They presented different time series analysis results including azimuth frequency modulation rate error, line of sight (LOS) ionospheric phase, azimuth shift caused by the ionosphere, and LOS displacement processed using both full-aperture and burst-by-burst workflows. The final InSAR LOS displacement time series result reveals both large-scale tectonic and small-scale anthropogenic deformation components. The results demonstrate the potential for measuring continental or even global-scale tectonic deformation and illustrate the promise of upcoming L-band wide-swath SAR missions such as NISAR.

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 following sections. 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.

Space Geodesy Network Deployment
SGP continued to advance the VLBI Global Observing System (VGOS) by operating its broadband VLBI stations at Kōkeʻe Park Geophysical Observatory (KPGO) in Hawaii, Goddard Geophysical and Astronomical Observatory (GGAO) in Maryland, and Westford in Massachusetts. SGP led numerous test sessions with several European and Japanese stations that were under commissioning. The NASA VGOS stations all participated in the CONT17 continuous VLBI campaign for five consecutive 24-hour observing sessions at the end of 2017. This campaign represents a major milestone as the first major VGOS session that will produce official geodetic products.

The University of Texas began building the facilities for the new multi-technique McDonald Geodetic Observatory in Texas. The build of the new NASA VGOS antenna and its signal chain is underway and is scheduled for implementation at the site beginning in the Fall of 2018 with commissioning in early 2019. SGP also began the manufacture of three Gimbal and Telescope Assemblies for the first three next-generation SLR stations, the first of which will be implemented at McDonald.

Development for the new NASA SLR station in Ny-Ålesund, Svalbard began under an agreement with the Norwegian Mapping Authority. The unique station location above the Arctic Circle will be particularly valuable in supporting the tracking of NASA's polar orbiting satellites. The SGP also continued to work with CNES on the implementation plan for a new joint NASA-CNES geodetic site in Tahiti.

Modernization of NASA's Global GNSS Network (GGN), initiated in 2016, is complete. Modernized GGN stations will provide NASA and the public with access to measurements from all major GNSS constellations (GPS, GLONASS, BeiDou, and Galileo), and ensures that the Network can support GPS Block III measurements.

SGP Data and Analysis
It was another record year for NASA Space Geodesy Network operations, and utilization of attendant data products. The NASA Satellite Laser Ranging (SLR) network 2017 annual total data yield increased by 31% over 2016 with over 44,000 satellite pass segments tracked. The legacy VLBI network made 1,039,314 observations in 2017, more than double the annual observations a decade ago. VLBI observations scheduled and analyzed by SGP during 2017 reduced the formal error by over 50% in 3300 under-observed sources, and a new VLBI Intensive observation strategy was developed that reduces the formal error for Universal Time (UT1) from 13.5 µs to 10.8 µs. The next generation VGOS network had 235,155 scheduled observations in 2017, more than 3 times the number in 2016. NASA's global space geodesy data archive and distribution system, the Crustal Dynamics Data Information System (CDDIS), had another year of record growth, breaking last year's data distribution figures by 20% with 1.7 billion file downloads from 260,000 unique users in 2017.

The International Terrestrial Reference Frame (ITRF) provides the foundation for measuring changes in the shape of the solid Earth, it's oceans, and atmosphere. The ITRF is also common to precise position and timing applications. The ITRF is updated every 5 – 7 years using the latest, best input data in order to maintain its precision and accuracy. The next update is scheduled for 2020 and NASA/JPL is completing software to produce a candidate solution. The new software will provide significant improvements in operability and flexibility in data analysis and this combination will allow researchers to search for more optimal solutions than in the past.

NASA/JPL has completed reprocessing all GPS orbits and clock estimates for the entire length of the GRACE mission, using the latest ITRF and models. The GPS orbit and clock estimates are a critical input into the interpretation and analysis of GRACE flight data and the new GPS products will be used in the final analysis of flight data from the GRACE mission, which ended this year.

SGP International Coordination

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 Geospatial Information Management (UN-GGIM), provides a forum for the enhancement and sustainability of the global geodetic reference frame (GGRF). Members of SGP are serving on working groups to help develop the Implementation Plan for the Global Geodetic Reference Frame Roadmap. The plan will be presented at the UN in August 2018 in New York City. The Roadmap and Implementation Plan are key tools to increase and focus international participation in meeting the world's needs for high quality geodetic products.

Richard Gross of NASA/JPL was elected Chair of the Global Geodetic Observing System (GGOS) in 2017. Since then, GGOS has embarked on two major efforts toward realizing its goals for improving the quality of geodetic products. First, GGOS is developing a set of "Essential Geodetic Variables" with the end goal of defining key performance requirements for each of the Space Geodesy techniques (GNSS, DORIS, SLR, and VLBI). Second, GGOS has expanded opportunities for participation by admitting national and regional organizations to join as GGOS Affiliates.

SGP Contributions to Broad Science Mission Directorate Objectives

New auxiliary laser beacons were installed on the MOBLAS-4 Satellite Laser Ranging (SLR) station in California and the MOBLAS-7 SLR station at GGAO in support of the Geostationary Operational Environmental Satellite (GOES) Geostationary Lightning Mapper (GLM). The beacons were successfully used to provide simulated lightning pulses for both GOES-16 and GOES-17 that help improve the geolocation of the GLM lightning detections.

SGP also supported the development of the 3rd realization of the International Celestial Reference Frame (ICRF-3) that is expected to be approved by the International Astronomical Union (IAU) and go into effect by January 2019.

Space Geodesy Research

Griffiths (2018: *J. Geodesy*) described the orbit and clock submissions and their combinations and assessments for the second reprocessing of the International GNSS Service (IGS) large global network of GPS tracking data from 1994.0 until 2014.0 or later. The orbits support long-term stable user solutions when used with network processing with either double differencing or explicit clock estimation. Among the main benefits of the reprocessing effort is a more consistent long product set to analyze for sources of systematic error and accuracy. Work to do that is underway, and the reprocessing experience has pointed to a number of ways future IGS performance and reprocessing campaigns can be improved.

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.

ESI coordinated and is sponsoring a new National Academy of Sciences study *Evolving the Geodetic Infrastructure to Meet New Scientific Needs* (http://dels.nas.edu/Study-In-Progress/Evolving-Geodetic-Infrastructure-Meet/AUTO-6-64-46-Y). The panel will carry out a study, organized around a workshop, to identify key connections between geodesy and priority Earth science questions as identified in the Decadal Survey (NASEM, 2018), and explore how to improve the geodetic infrastructure to meet new science needs. This study is co-funded by ESI and the Physical Oceanography and Cryospheric Sciences programs and is being carried out as a collaboration among the National Academies Board on Earth Sciences and Resources, Space Studies Board, Board on Atmospheric Sciences and Climate, Polar Research Board, Ocean Studies Board, and Water Science and Technology Board.

ESI also supported and helped lead a number of meetings geared towards readiness for the NISAR mission. The focus area co-funded with NSF the workshop *Hydro-Geodesy: Hydrological applications of geodetic techniques* in San Diego, CA, in October 2017, and supported the *InSAR Atmospheric Applications Workshop* at the University of Maimi in March 2018. The latter workshop brought together atmospheric scientists interested in using NISAR interferograms as data to feed their weather models. Several NISAR applications workshops were also held throughout the year, including on *Critical Infrastructure (FEMA/DHS)* in Crystal City, VA, in October 2017; *Forest Structure and Biomass (USDA/USFS)* in Washington, DC, in June 2018; and *Agriculture and Soil Moisture (USDA)* in Beltsville, MD, in June 2018.

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FY 2018 Annual Performance Indicator	FY 15	FY16	FY17	FY18
ES-18-11: 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.	Green	Green	Green	Green