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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Annual Performance Indicator ES-19-1: 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.

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 to gain insights into changes in the Earth's radiation balance, our prognostic capability for the recovery of stratospheric ozone and its impacts on surface ultraviolet radiation, and the evolution of greenhouse gases and their impacts on climate, as well as the evolution of tropospheric ozone and aerosols and their impacts on climate and air quality. The ACFA research utilizes and coordinates advances in observations, data assimilation, and modeling to better understand the Earth as a system. Selected research results and other accomplishments of the 2019 financial year are highlighted below.

Aerosol and cloud radiative effects research

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

Volcanic impact on the climate – the stratospheric aerosol load in the period 2006–2015

Accurate measurements of stratospheric aerosol optical depth have been obtained from a multi-decade series of SAGE solar occultation instruments. These measurements have been continuous since the 1980's, except for a gap between the end of SAGE II in 2005 and the start of the SAGE III record in 2017. Friberg et al., (2018) analyzes CALIPSO observations from 2006 to 2015 to fill in this gap. The paper constructs a record of aerosol optical depth from the tropopause to the mid-stratosphere and estimates the climate forcing from stratospheric aerosol over the period. They identify volcanic influences on stratospheric aerosol loading, finding a 40% increase in stratospheric aerosol forcing during 2006-2015 due to a series of moderate volcanic eruptions amounting to an increased cooling of 0.2 W/m2. This represents an important observational constraint on radiative forcing of the climate over recent decades.

Radiative forcing and stratospheric warming of pyrocumulonimbus smoke aerosols

Smoke particles can be injected by pyrocumulonimbus in the upper troposphere and lower stratosphere (UTLS), but their effects on the radiative budget of the planet remain elusive. Christian et al., (2019) focused on the record-setting Pacific Northwest pyrocumulonimbus event of August 2017, and showed with satellite-based estimates of pyrocumulonimbus emissions and injection heights in a chemical transport model (GEOS-Chem) that pyrocumulonimbus smoke particles can result in radiative forcing of 0.02 W/m2 at the top of the atmosphere averaged globally in the two months following the event and up to 0.9 K/day heating in the Arctic Upper Troposphere - Lower Stratosphere (UTLS). The modeled aerosol distributions agree with observations from satellites (EPIC, CATS, and CALIOP), showing the hemispheric transport of pyrocumulonimbus smoke aerosols with a lifetime of 5 months. Hence, warming by pyrocumulonimbus-s aerosols can have similar temporal duration as but opposite in sign of the well-documented cooling of volcanic aerosols, and be significant for climate prediction.

Evaluation of the vertical distribution of radiative heating rates in climate models and by observations

The vertical distribution of radiative heating rates depends on cloud amount and properties. Their representation in climate models is often imperfect. By comparing cloud vertical distributions between models and lidar-radar (CALIPSO & Cloudsat) combined observations, Cesana et al., (2019) found systematic differences in the form of an excess of high-level clouds around 200 hPa in the tropics and a general lack of mid- and low-level clouds in model output compared to observations. The excess clouds and ice water content in the upper troposphere result in excess infrared heating in the vicinity of and below the clouds as well as a lack of solar heating below the clouds. In the lower troposphere, the smaller cloud amount and the underestimation of cloud-top height is coincident with a shift of the infrared cooling to lower levels, which substantially reduces the greenhouse effect. The reduced greenhouse effect is slightly compensated for by an erroneous excess absorption of solar radiation. Clear-sky radiative heating rate differences between the observations and models mitigate cloudy radiative heating rate biases at low levels while they enhance them at high levels.

A different study by Wang et al., (2019) investigated the statistics of vertical ice cloud microphysical structure obtained from 1-year of CloudSat and CALIPSO data. These data fed a forward radiative transfer model whose output was used in a MODIS-like ice cloud retrieval. The impact of vertical heterogeneity focused on IWP retrievals and radiative flux calculations. While IWP biases using the statistical dataset can be large (−35% bias in MODIS monthly IWP for global ice clouds over ocean), radiative impacts were relatively minor (<< 1 W/m2).

Estimates of global shortwave direct aerosol radiative effects above clouds

Using passive sensors to retrieve aerosol located above clouds is very difficult. Further, models do a poor job of simulating the vertical distribution of aerosol. Estimates of the amount of aerosol found above clouds is very uncertain, and the radiative impacts of aerosol above cloud are something of a wild card in estimates of aerosol climate forcing. Kacenelenbogen et al., (2019) uses profile data from CALIPSO to estimate the direct radiative effect of aerosol above opaque water clouds. To avoid some of the limitations of the standard CALIPSO retrievals, they apply a technique where the AOD above cloud is derived directly from the integrated lidar return from opaque water clouds. This is the first study to characterize the radiative effects of aerosol above cloud on a global basis, finding half a dozen regions around the globe where aerosol is frequently found above cloud. The global mean radiative effect is found to be a net warming of 0.20 W/m^2.

Constraining longwave cloud feedback from space

A study by Vaillant de Guélis et al., (2018) builds on a series of previous papers which develop and validate a means of estimating longwave cloud radiative effects from CALIPSO lidar returns. In this paper, this method is used to study longwave cloud radiative feedback through analysis of cloud changes over the 2008-2014 period. A lidar satellite simulation for model assessments is used to allow consistent comparisons of simulations from a climate model with CALIPSO observations from CALIOP. Changes in longwave cloud radiative effects can be ascribed to changes in cloud altitude, cloud cover, and cloud opacity in both observations and model. The observed cloud feedback over 2008-2014 is found to have the opposite sign from that simulated in the model. The model is found to adequately simulate observed changes in cloud altitude, but significantly underestimates observed changes in cloud cover. These results point to areas where the model physics may be lacking and where improved cloud parameterizations could provide more accurate climate predictions.

Important but uncertain is the atmospheric pathway of the cloud-radiative impact on the circulation response to global warming

Voigt et al., (2019) used an ensemble of global climate models to study the impacts of changes in cloud radiative heating on the large-scale circulation of the atmosphere. It is found that roughly half the changes in atmospheric circulation are due to direct impacts of cloud radiative heating and the other half due to cloud-induced changes in sea surface temperature. Circulation changes driven by changes in high-level clouds are robust across the model ensemble, but the magnitude of the changes varies significantly between models. Upper-tropospheric radiative heating by high-level clouds in the present-day climate derived from CALIPSO-CloudSat observations are used to identify weaknesses in the radiative heating by high level clouds predicted by the models. Improvements in the model representation of radiative heating of high clouds will reduce uncertainties in predicted circulation changes, leading to improved predictions at regional scales.

The diurnal cycle of cloud and aerosol profiles between 51° S and 51° N

A study by Noel et al., (2018) analyzed vertical profiles of cloud fraction (CF) using 15 months of data from the Cloud-Aerosol Transport System (CATS) lidar on the non-sun-synchronous International Space Station (ISS). They found few high clouds during daytime over the tropical ocean in summer. At night, however, high clouds become frequent over a large altitude range (11–16 km between 22:00 and 04:00 LT). During the summer, over tropical continental regions, but not over ocean, mid-level clouds (4–8 km above sea level) were found to persist all day, with a weak diurnal cycle (minimum at noon). Over the Southern Ocean, diurnal cycles appear for the omnipresent low-level clouds (minimum between noon and 15:00) and high-altitude clouds (minimum between 08:00 and 14:00). Both cycles are time shifted, with high-altitude clouds following the changes in low-altitude clouds by several hours. Over all continents at all latitudes during summer, low-level clouds develop and reach a maximum occurrence at about 2.5 km above sea level in the early afternoon (around 14:00). These results are useful for better constraining cloud parametrizations in climate models.

Another study by Lee al., (2018) investigated the global aerosol diurnal variations with CATS data. They found marginal variations in AOD from a global mean perspective, with the maximum and minimum aerosol vertical profiles found at local noon and 6:00 pm local time respectively, for both the June–November and December–May seasons. Strong diurnal variations are found over North Africa and India during December to May, and over North Africa, Middle East, and India during June to November. In particular, over North Africa, during June to November, a diurnal peak in aerosol extinction profile 20% larger than the daily mean is found at 6:00 AM (early morning local time), which may possibly be associated with dust generation through the breaking down of low-level jet during morning hours.

Effects on deep convective clouds by different types of aerosols

Convective clouds produce a significant proportion of the global precipitation and play an important role in the energy and water cycles. From CloudSat and CALIPSO observations, Jiang et al., (2018) found that aerosols can inhibit or invigorate convection, depending on aerosol type and concentration. On average, smoke tends to suppress convection and results in lower cloud altitudes than clean clouds. Polluted continental aerosol particles tend to invigorate convection and promote higher cloud altitudes. Dust aerosol effects are regionally dependent and their signs differ from place to place in South America, Central Africa and Southeast Asia. Moreover, Jiang et al., (2018) found the aerosol inhibition or invigoration effects do not vary monotonically with aerosol optical depth and the variations depend strongly on aerosol type. Observational findings indicate aerosol type is one of the key factors in determining aerosol effect on convective clouds.

In-situ aerosol property information

Espinosa at al., (2019) used the generalized inversion algorithm GRASP to retrieve fundamental particle properties like size, shape and optical constants (complex refractive index) from airborne measurements of the angular scattering and absorption of light by aerosol particles. These investigators found the particles emitted from wild fire, urban and botanical sources were generally similar in size and shape but differed significantly in their refractive index. They also found aerosols in close proximity to storm systems had higher concentrations of large particles, likely soil and dust emanating from Earth's surface as a result of winds associated with these systems. These data constitute a uniquely comprehensive picture of aerosol properties and can inform assumptions used in space-based aerosol retrievals and climate models.

Intercomparison of aerosol size between AERONET retrievals and aircraft samples

The Aerosol Robotic Network (AERONET) aerosol monitoring network is the community standard for the validation of aerosol remote sensing retrievals. AERONET provides direct measurements of aerosol optical depth (AOD) and retrievals (indirect measurements using inversions from almucantar scans of radiance as a function of scattering angle) of aerosol microphysical properties, such as aerosol volume size distribution, aerosol complex refractive index, optical absorption (single scattering albedo) and the aerosol scattering phase function. All these products represent an average of the total aerosol column within the atmosphere. The inversion-based products need to be validated against aerosol in-situ aircraft profile measurements to validate their accuracy before they can be used for satellite data validations as well. The latest and most extensive comparisons of AERONET size distribution retrievals with aircraft sampling of particle size was analyzed and published by Schafer at al., (2019). After correction for measurement biases (AERONET observes aerosols at ambient humidity, while the NASA Langley Aerosol Group Experiment's (LARGE) Ultra-High Sensitivity Aerosol Spectrometer (UHSAS) sampling instrument operates on dried aerosols), the study finds 5% larger values by AERONET for aerosol radius during peak concentrations and 16% larger values by AERONET for fine mode aerosol volume size distribution.

Extreme aerosol optical properties observed during Indonesian biomass burning event

An extreme biomass burning event occurred in Indonesia from September through October 2015 due to severe drought conditions, partially caused by a major El Niño event. The significant burning of peatland affected public health and caused severe economic and environmental damage. This event had the highest sustained aerosol optical depths (AOD) ever monitored by the global Aerosol Robotic Network (AERONET) of up to approximately 7 at 675 nm (Eck at al., 2019), which corresponds to the upper limit of Sun photometry. Measured AEs at the highest monitored AOD levels were subsequently utilized to estimate instantaneous values of AOD at 550 nm in the range of 11 to 13, well beyond the upper measurement limit and higher than previously reported in the scientific literature. Retrievals of single scattering albedo were utilized to estimate that 85% of the AOD was from peat land burning, which is in excellent agreement with independent estimates. Such extreme aerosol events literacy blur the boundaries between clouds and aerosol for aerosol remote sensing techniques. For example, the MODIS Dark Target aerosol algorithm underestimated the regional AOD during this event on average by approximately 0.2 and up to 3.0 in a few individual retrieval grid boxes (Shi et al., 2019). This underestimation can skew the perception of the severity of such significant events, affect estimates of regional aerosol forcing, and alter aerosol modeling and forecasting that assimilate remote sensing aerosol data products.

Climatology of Asian dust activation and transport potential

The relative contribution of the Taklamakan and Gobi deserts to dust loadings through long-range transport is addressed in an observational study by Yu Y. et al., (2019). Stereo observations of dust sources from MISR combined with observation-initiated trajectory modeling are used. MISR-derived dust plume top height and dust plume motion vectors confirm the peak of dust activation and transport potential in spring over the Gobi Desert and in both spring and summer over the Taklamakan Desert. Long-range trajectory patterns of Asian dust, including the influence on North America through trans-Pacific transport, are assessed using forward trajectories initiated by MISR dust plume observations. The trajectory patterns show substantial seasonal and interannual variability. Trajectory analysis reveals latitude-dependent spread of dust trajectories from the Taklamakan and Gobi deserts, with Taklamakan dust dominant southward of 50ºN and Gobi dust dominant northward of 50ºN in North America.

AOD trends and estimates of African dust deposition during transatlantic transit

Yu H. et al., (2019) analyzed both MODIS satellite and CAM5 model data for interannual variability and trends of combustion and dust aerosol optical depth (AOD) in major continental outflow regions for the years 2003 to 2017. Both satellite and model data sources consistently show a decreasing trend for combustion AOD over the North Atlantic Ocean and the Mediterranean Sea and an increasing trend over the tropical Indian Ocean, the Bay of Bengal, and the Arabian Sea. Over the northwestern Pacific Ocean, which is affected by both pollution and dust, both combustion and dust AOD decreased in the MODIS retrievals, but not the CAM5 model. In other outflow regions of smoke and/or dust, neither MODIS observations nor CAM5 simulations show statistically significant trends. The MODIS observed interannual variability is usually larger than that of the CAM5 simulation.

Review of polarimetric remote sensing of atmospheric aerosol particles

Dubovik et al., (2019) provides and overview of different techniques and instrument capable of polarimetric observations, their history and expected developments, and the state of resulting aerosol products. The paper also discusses the main achievements and challenges in the exploitation of polarimetry for the improved characterization of atmospheric aerosols. This review paper offers a valuable summary of polarimetric instruments and methods, which are relevant in the context of upcoming NASA PACE and MAIA missions, as well as EUMETSAT's METOP satellite. These results can also inform NASA's pre-formulation study on the Designated Observable of the 2017 Decadal Survey mission Aerosol, Clouds, Convection, and Precipitation (ACCP). More details on the complementary multi-angle polarimeters for the space-based retrieval of global aerosol properties by the PACE mission are reviewed in Remer et al., (2019). This paper includes the history, present and future of satellite sensors that observe multi-spectral, multi-angular, and multi-state (nonpolar and polarized) reflected solar radiation, along with algorithms that exploit this information for retrieving properties of aerosol properties. The path forward is likely to involve joint retrievals that will simultaneously retrieve aerosol and surface properties. However, advances in radiative transfer modeling will be required. For example, representation of optically complex constituents and developing the processing capability to handle global scale observations.

A new observable using existing data: marine liquid cloud geometric thickness

It is key for the climate science and weather forecasting community to improve our understanding of the linkages between radiative and dynamic processes, as well as the water cycle in the atmosphere. Richardson et al., (2019) introduced a novel observable on the liquid cloud geometric thickness over oceans. It uses the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) lidar and the Orbiting Carbon Observatory-2 (OCO-2) hyperspectral A-band spectrometer. CALIPSO provides a prior cloud top pressure for an OCO-2-based retrieval of cloud optical depth, cloud top pressure and cloud geometric thickness expressed in hPa. Measurements are of single-layer liquid clouds over oceans from September 2014 to December 2016 when collocated data are available. Retrieval performance is best for solar zenith angles $<45^{\circ}$ and when the cloud phase classification, which also uses OCO-2's weak CO_2 band, is more confident. The highest quality optical depth retrievals agree with those from the Moderate Resolution Imaging Spectroradiometer (MODIS) with discrepancies smaller than the MODIS-reported uncertainty. Retrieved thicknesses are consistent with a substantially subadiabatic structure over marine stratocumulus regions, in which extinction is weighted towards the cloud top. Cloud top pressure in these clouds shows a 4 hPa bias compared with CALIPSO which can be attributed mainly to the assumed vertical structure of cloud extinction after showing little sensitivity to the presence of CALIPSO-identified aerosol layers or assumed cloud droplet effective radius. This is the first case of success in obtaining internal cloud structure from hyperspectral A-band measurements and exploits otherwise unused OCO-2 data. This retrieval approach should provide additional constraints on satellite-based estimates of cloud droplet number concentration from visible imagery, which rely on parameterization of the cloud thickness.

EPIC: glint over land & how Earth observation can help finding habitable exoplanets

Small flashes of reflected light—called glint—are found regularly in images taken by spacecraft observing the Earth, and occur due to specularly reflected solar radiation. While glint over water surfaces (oceans, but also lakes and rivers) are common, Li et al. (2019) found glint in Earth Polychromatic Imaging Camera (EPIC; Marshak et al., 2018) images also over land. Using the Deep Space Climate Observatory (DSCOVR spacecraft that is orbiting the gravitational plus centrifugal force balance point Lagrangian-1, which affords a continuous view of the "Earth at noon.") observations, they show glint over land is due to specular reflection off horizontally oriented ice platelets floating in the air, while glint over ocean have contributions from reflection off either platelets floating above the ocean or a relatively smooth ocean surface. Marshak et al., (2018) used a radiative transfer model to simulate different kinds of glint and to explore their properties. This technique of comparing observations of terrestrial glint with model simulations may provide new information, not only for Earth sciences but also for planetary sciences, on atmospheric dynamics and the search for habitable exoplanets. Similarly, the NISTAR instrument on DSCOVR observes seasonal changes in Earth's total outgoing radiation. The radiation energy balance measurement is important because it is the fundamental energy constraint on climate models, and difficult because reflected solar and emitted thermal radiation depend strongly on the viewing geometry. NISTAR's unique viewing geometry for monitoring the Earth's energy budget amounts to observing the Earth as an exoplanet, which opens a new perspective on exoplanet observation (Carlson et al., 2019).

Further science using EPIC on DSCOVR is described by Su et al., (2018) on shortwave radiative flux and by Herman et al., (2018b) on O_3, SO_2, aerosol properties, cloud reflectivity, and erythemal irradiance (integrated UV irradiance at the ground relevant to effects on the human skin).

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 (e.g. PM monitors, Pandora spectrometers) with chemical transport models is expected to enhance the capabilities and accuracies of urban air quality data used in forecasts and health studies.

Harmful air quality observed over Seoul

The Korean Peninsula has experienced degradation in air quality both from rapid increases in local emissions and influences from external sources. As part of the Korea–United States Air Quality Study (KORUS-AQ) research, Miyazaki et al, (2019) ingested the Aura, as well as GOME-2 and MOPITT data and new AIRS/OMI ozone (Fu et al, 2018) into a chemical data assimilation system to quantify the balance of meteorology and local emissions on Korean air quality. They showed that NO_x and CO emissions were 40% and 83% higher, respectively, than previous inventories leading to an increased mean ozone concentration by up to 7.5 ± 1.6 ppbv. They further showed that mean ozone concentrations were persistently higher over Seoul (75.10 ± 7.6 ppbv) than the broader KORUS-AQ domain (70.5 ± 9.2 ppbv) at 700 hPa.

Spinei et al. (2018) published a first evaluation of formaldehyde (HCHO) column observations derived from Pandora ground-based spectrometer measurements with NASA vertical distributed DC-8 in-situ sampling in the lower troposphere (0–5 km). The results show diurnal variation in HCHO total column densities followed the same pattern at both sites, with the minimum daily values typically observed between 6:00

and 7:00 local time, gradually increasing to a maximum between 13:00 and 17:00 before decreasing into the evening. A comparison between 49 column densities measured by Pandora vs. aircraft-integrated in situ data showed that Pandora values were larger by 16 % with a constant offset of 0.22 DU (Dobson units; r^2=0.68). Further results suggest that diurnal changes in HCHO surface concentrations can be reasonably estimated from the Pandora total column and information on the mixed-layer height.

Herman et. al. (2018a) published findings from nine Pandora spectrometers installed at eight sites in South Korea as part of the KORUS-AQ integrating information from ground, aircraft, and satellite measurements for validation of remote sensing air-quality studies. Retrieval of formaldehyde (HCHO) total column amounts were also obtained at five sites. Pandora spectrometer direct-sun retrieved values for NO_2 and HCHO are found significantly larger than OMI (AURA satellite Ozone Monitoring Instrument) retrieved NO_2 and HCHO. In urban areas, Pandora spectrometer NO_2 30-day running averages are at least a factor of two larger than OMI averages. Similar differences are seen for HCHO in Seoul and nearby surrounding areas. Late afternoon values of HCHO measured by Pandora spectrometers are even larger, implying that OMI early afternoon measurements underestimate the effect of poor air quality on human health. The primary cause of OMI underestimates is the large OMI field of view that includes regions containing low values of pollutants. Comparisons of Pandora HCHO results were made with the Compact Atmospheric Multispecies Spectrometer CAMS during overflights on the DC-8 aircraft for Taehwa Mountain and Olympic Park. In all cases, Pandora measured substantially more HCHO than obtained from integrating the CAMS altitude profiles. Pandora HCHO data at Yonsei University in Seoul frequently reached 0.6 DU and occasionally exceeded 1.5 DU. The semi-rural site, Taehwa Mountain, frequently reached 0.9 DU and occasionally exceeded 1.5 DU. Even at the cleanest site, Amnyeondo, HCHO occasionally exceeded 1 DU.

The impact of spatial resolution on tropospheric NO_2 retrievals in urban areas

Localized pollution of NO_2 changes on small spatial scales. The spatial resolution of satellite measurements is often too coarse to identify individual sources. Judd et al, (2019) found when comparing ground-based Pandora reference data with simulated TEMPO, TROPOMI, and OMI data that the aircraft-to-Pandora slope degrades from 0.88, 0.77, and to 0.57, respectively. The satellite data were derived from airborne the UV/Visible spectrometer GeoTASO data acquired over the western shore of Lake Michigan and over the Los Angeles Basin. The direct comparison of the full-resolution (250x250 m) GeoTASO data with Pandora reference data shows good agreements with r^2=0.91 and slope of 1.03. This confirms the notion of a need for high spatial resolution observations to adequately capture the spatial heterogeneity of urban pollution sources.

Connecting in-situ and Satellite Monitoring in Support of the Canada – U.S. Air Quality Agreement

In the June 2019 issue of the Air and Waste Management Association's *Energy Management*, Szykman et al. (2019) published an article highlighting how the United

States Environmental Protection Agency (EPA) and Environment and Climate Change Canada (ECCC) are using Pandora as the backbone for their continued support of the Canada-US air quality agreement. Both agencies are using Pandora to assist in the characterization and validation of satellite data as well as to monitor and assess emissions and transport of air pollution over the vast areas that contribute to transboundary pollution. The article also provides an outlook for the critical role the emerging Pandonia Global Network will play in the standardization of Pandora systems worldwide and supporting both the EPA and ECCC in their monitoring and research activities.

Space-based NO_2 as a proxy for economic growth over populous global cities

A recent study by Montgomery and Holloway (2018) examines the relationship between economic growth and air quality (nitrogen oxides, NO_x, as an indicator) in the 100 most populated global cities, based on satellite nitrogen dioxide (NO_2) data from the Ozone Monitoring Instrument (OMI) on the Aura satellite and gross urban product (GUP). For the time period of 2005-2011 differences were found between those cities considered low-income and those denoted as high-income cities with the later having decreasing NO_2. This is likely due to air pollution controls despite economic growth (increasing GUP). The lower income cities showed increasing NO_2 with industrialization, urbanization, and increasing energy consumption indicative of rapid economic growth.

Increasing anthropogenic emissions of volatile organic compounds and decreasing agricultural fire emissions in China

Satellite observations of formaldehyde (HCHO) are used as a proxy to detect emissions of volatile organic compounds (VOCs), which are of concern for air quality. 2005–2016 satellite observations of HCHO over China are used to infer trends in VOC emissions. A 13% increase was found in the North China Plain and 18% in the Yangtze River Delta (Shen et al., 2019), consistent with the trend of anthropogenic VOC emissions in the Multi-resolution Emission Inventory for China (MEIC). Unlike other pollutants, emissions of VOCs in China have not decreased in recent years. An exception is the Huai River Basin in rural eastern China where the satellite data show rapidly decreasing VOC emissions since the early 2010s that appear to reflect bans on agricultural fires.

Indian ambient air quality standard is achievable by mitigating emissions from household sources

A MISR-derived $PM_{2.5}$ dataset was used by Chowdhury et al., (2019) to model how annual $PM_{2.5}$ exposure would change if household sources (biomass burning for cooking and heating, and kerosene lighting) were completely mitigated. Based on this model, complete elimination would reduce annual premature deaths in India by 6.6% for cooking sources, 5.5% for heating sources, and 0.6% for lighting sources. 103 districts in India would meet the country's annual air quality standards for the first time, and the country as a whole would meet the annual air quality standard.

Estimates of the global burden of ambient $PM_{2.5}$, ozone, and NO_2 on asthma incidence and emergency room visits

Environmental Health Perspectives published a recent report in which Anenberg et al., (2018) aimed to estimate the number of asthma emergency room visits and new onset asthma cases globally attributable to fine particulate matter ($PM_{2.5}$), ozone, and nitrogen dioxide (NO_2) concentrations. Estimates of global 2015 surface NO_2 were derived from Aura OMI NO_2 and the NASA Goddard GMI-Replay chemical transport model. The authors estimated that 9–23 million and 5–10 million annual asthma emergency room visits globally in 2015 could be attributable to ozone and $PM_{2.5}$, respectively, representing 8–20% and 4–9% of the annual number of global visits, respectively. The range reflects the application of central risk estimates from different epidemiological meta-analyses.

Global organic aerosol schemes evaluated with airborne observations

Chemical transport models have historically struggled to accurately simulate the magnitude and variability of observed organic aerosol (OA). Previous studies demonstrate models significantly underestimate observed concentrations in the troposphere. A more recent evaluation of global OA schemes using airborne observations was published by Pai et al. (2019). Two different model OA schemes are explored within the standard GEOS-Chem chemical transport model. The simulations are evaluated to data from a suite of 15 globally-distributed airborne campaigns from 2008–2017 (ATom, KORUS-AQ, GoAmazon, FRAPPE, SEAC4RS, SENEX, DC3, CalNex, OP3, EUCAARI, ARCTAS and ARCPAC). The OA schemes include a "simple scheme" that models primary OA (POA) as non-volatile and takes a fixed-yield approach to secondary OA (SOA) formation, and a "complex scheme" that simulates POA as semi-volatile and uses a more sophisticated volatility basis set approach for non-isoprene SOA, with an explicit aqueous uptake mechanism to model isoprene SOA. Despite these substantial differences, both the simple and complex schemes perform comparably across the aggregate dataset in their ability to capture the observed variability. The simple scheme displays greater skill in minimizing the overall model-bias. However, significant differences exist in model performance across different chemical source regimes. Higher-resolution nested regional simulations indicate model resolution is an important factor in capturing variability in highly-localized campaigns, while also demonstrating the importance of well-constrained emissions inventories and local meteorology, particularly over Asia. While this study identifies factors within the SOA schemes that likely contribute to OA model bias (such as a strong dependency of the bias in the complex scheme on relative humidity and sulfate concentrations), comparisons with the skill of the sulfate aerosol scheme in GEOS-Chem indicate the importance of other drivers of bias such as emissions, transport, and deposition that are exogenous to the OA chemical scheme.

Towards the atmospheric composition geostationary satellite constellation

The Korean Geostationary Environment Monitoring Spectrometer (GEMS) will be launched over Asia in February of 2020 as the first member of the geostationary satellite constellation to monitor Northern Hemisphere atmospheric composition for basic research, and for air quality forecast, health and management applications. GEMS will later be joined by the NASA EVI-1 TEMPO instrument over North America and ESA Sentinel 4 over Europe. These instruments will have similar measurement capabilities to observe pollutant trace gases and aerosol in the UV-visible range, every hourly at the high spatial resolution. Kim J. et al., (2019) describes the GEMS mission, measurement objectives and expected performance. The Korean, US and European teams are working together on joint algorithmic, calibration, data and validation approaches to ensure consistency among the constellation products. It is expected that the new geostationary observations for atmospheric composition will revolutionize air quality forecasting with an impact similar to that produced by the first meteorological geostationary satellites on weather forecasting over four decades ago.

Satellite-based sulfur dioxide observations are found useful by the cleantech sector

Space-based sulfur dioxide (SO_2) observations were used by Ialongo et al., (2018) to evaluate the efficacy of cleantech solutions in reducing air polluting emissions from metal smelting. The authors analyzed the Ozone Monitoring Instrument (OMI) satellite-based SO_2 observations over Tsumeb (Namibia) and Bor (Serbia) copper smelters, where two sulfur-capture plants, designed to transform gaseous SO_2 emissions into sulfuric acid, were implemented in 2015. They observed a reduction in the annual SO_2 emissions by up to 90% after 2015 at both smelters, as a result of the implementation of the sulfuric acid plants. Output of this study was directly used by the company operating the sulfuric acid plants to confirm the efficacy of the employed technology using independent OMI-based SO_2 observations.

New global anthropogenic SO_2 emission inventory for the last decade

Atmospheric Chemistry and Physics published a study in which Liu et al., (2018) combined satellite-based emissions of sulfur dioxide (SO_2) for large sources with a bottom-up inventory derived from reported fossil fuel combustion for smaller sources, to construct a new "merged" inventory. Model simulations using the merged inventory show normalized mean bias (compared to observed SO_2 at monitoring stations) dropped from 0.29 to 0.05. The new merged emission database can be used on its own to capture the spatial and temporal variations in SO_2 emissions and can also be used to support climate and air quality modelling.

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.

The 2015–2016 carbon cycle as seen from OCO-2 and the global in situ network

Orbiting Carbon Observatory-2 (OCO-2) reveal new information about the carbon cycle through the use of top-down atmospheric inversion methods combined with column average CO_2 retrievals. Crowell et al., (2019) quantified the satellite-informed fluxes from OCO-2 land observations (V7r) and their uncertainties at continental scales using an ensemble of atmospheric inversions utilizing different transport models, data assimilation techniques and prior flux distributions. The comparison against in-situ measurements shows that within ensemble spread, in situ observations and satellite retrievals constrain a similar global total carbon sink of 3.7 ± 0.5 petagrams C, and 1.5 ± 0.6 petagrams C per year for global land, for the 2015–2016 annual mean. This agreement, however, breaks down on smaller regions. For example, differences occurring in tropical Africa could be an indication of the global perturbation from the 2015–2016 El Niño. Those are potentially important findings because tropical ecosystems store large amounts of carbon, but are particularly vulnerable to changes in climate. Evaluation of posterior concentrations using TCCON and aircraft observations gives some limited insight into the quality of the different assimilation constraints, but the lack of such data in the tropics inhibits our ability to make strong conclusions there.

Four years of global column CO_2 anomalies as seen by Orbiting Carbon Observatory-2

Data collected by the Orbiting Carbon Observatory-2 (OCO-2) between 2015 and 2018 were analyzed by Hakkarainen et al., (2019) to identify regions with persistent CO_2 anomalies, where the column-averaged CO_2 dry air mole fraction (XCO_2) is significantly higher or lower than the background value. Positive anomalies are commonly seen over heavily developed regions with intense fossil fuel combustion, such as eastern and southern Asia, the eastern U.S., central Europe, and the Highveld region of South Africa. Somewhat more surprisingly, large, persistent positive XCO_2 anomalies are seen over tropical land in South America, Africa, and Oceania, suggesting these areas are now strong net sources of CO_2. In sharp contrast, most carbon cycle models assume that these regions are strong CO_2 sinks. Meanwhile, the largest negative XCO_2 anomalies are seen during the growing seasons over northern hemisphere continents (Asia, North America). These results clearly show that space-based CO_2 data from OCO-2 can be used to monitor both natural and anthropogenic CO_2 sources and sinks.

Net carbon emissions from African biosphere dominate pan-tropical atmospheric CO_2 signal

Tropical ecosystems are large carbon stores that are vulnerable to climate change. The sparseness of ground-based measurements has precluded verification of these ecosystems being a net annual source or sink of atmospheric carbon. Palmer et al. (2019) show that two independent satellite data sets of atmospheric carbon dioxide, interpreted using independent models, are consistent with the land tropics being a net annual carbon emission of median 1.03 and 1.60 petagrams C in 2015 and 2016, respectively. These pan-tropical estimates reflect unexpectedly large net emissions from tropical Africa of 1.48 petagrams C in 2015 and 1.65 petagrams C in 2016. The largest carbon uptake is over the Congo basin, and the two loci of carbon emissions are over western Ethiopia and western tropical Africa, where there are large soil organic carbon stores and where there has been substantial land use change. These signals are present in the space-borne CO_2 record from 2009 onwards.

Links between CO and climate indices for the Southern Hemisphere and tropical fire regions

In the Southern Hemisphere and tropics, the main contribution to carbon monoxide (CO) variability is from fire emissions, which are connected to climate through the availability, type, and dryness of fuel. With the aim to predict CO loading during fire seasons, Buchholz et al., (2018) assessed the relationships between CO and climate. Observations of total column CO from the Measurements Of Pollution In The Troposphere (MOPITT) satellite instrument are used to build a record of monthly anomalies between 2001 and 2016, focusing on seven biomass burning regions of the Southern Hemisphere and tropics. With the exception of 2015, the range of absolute variability in CO is similar between regions. Buchholz et al., (2018) finds that all climate mode indices (El Niño–Southern Oscillation, Indian Ocean Dipole, Tropical South Atlantic, and Antarctic Oscillation) are required to model CO in each region, generally explaining over 50% of the variability and over 70% for tropical regions. First-order interaction terms of the climate modes are necessary, producing greatly improved explanation of CO variability over single terms. Predictive capability is assessed for the Maritime Southeast Asia and the predicted peak CO anomaly in 2015 is within 20% of the measurements.

Anthropogenic and biogenic CO_2 fluxes in the Boston urban region

PNAS published a comprehensive analysis by Sergent et al., (2018) of CO_2 emissions in the urban domain of Boston and surrounding regions. The work establishes the template for monitoring and measuring fossil fuel emission from large urbanized areas, combining inverse modeling with extensive data from sensors on the ground, in aircraft, and from satellites. It introduced and validated new "big-data" approaches to determine actual emissions in an urban area, including spatial and temporal distributions. It lays the groundwork for OCO-3 measurements of urban emissions, which have the Boston urban domain as a principal early target.

The potential of combined AIRS and OMI retrievals to continue the TES record

Tropospheric ozone is an important air quality pollutant, greenhouse gas, and component of the atmospheric oxidative capacity that has been measured by two different spectral regions: infrared (IR) and ultraviolet (UV). Fu et al., (2018) showed that combining these two regions from AIRS and OMI in a unified retrieval system yields ozone profiles with higher vertical sensitivity than either instrument separately with biases consistent with the Tropospheric Emission Spectrometer (TES). These results show the potential of combined AIRS and OMI to continue the TES record but with two orders of magnitude higher spatial coverage.

Overview of the OCO-3 mission

The Orbiting Carbon Observatory-3 (OCO-3) is NASA’s next instrument dedicated to extending the record of the dry-air mole fraction of column carbon dioxide (XCO_2) and solar-induced fluorescence (SIF) measurements from space. It was launched on May 4, 2019 from the Kennedy Space Center via a Space-X Falcon 9 and Dragon capsule. The instrument is now installed as an external payload on the Japanese Experimental Module Exposed Facility of the International Space Station (ISS) with a nominal mission lifetime of 3 years. The orbit of the ISS allows for viewing of the Earth at all latitudes less than approximately 52º, with a ground repeat cycle that is much more complicated than the polar-orbiting satellites that so far have carried all of the instruments capable of measuring carbon dioxide from space. The grating spectrometer at the core of OCO-3 is a direct copy of the OCO-2 spectrometer, which was launched into a polar orbit in July 2014. As such, OCO-3 is expected to have similar instrument sensitivity and performance characteristics to OCO-2, which provides measurements of XCO_2 with high precision (<1 ppm at 3 Hz), with each viewing frame containing eight footprints approximately 1.6 km by 2.2 km in size. However, the 52º orbit and the physical configuration of the instrument aboard the ISS, as well as the use of a new pointing mirror assembly, will alter some of the characteristics of the OCO-3 data compared to OCO-2. Specifically, there will be significant differences from day to day in the sampling locations and time of day. In addition, the flexible pointing mirror assembly system allows for a much more dynamic observation-mode schedule. More details on the science objectives and a simulation of 1 year of global observations with the anticipated data quality are provided by Eldering et al., (2019).

Constrain climate projections with the snow-albedo feedback and statistics

Reducing the uncertainty in climate projections has been one of the signature challenges in Earth science because simulated future climate states cannot be directly falsified. Over the last decade, emergent constraints have become powerful techniques to use present-day observations to constrain future climate projections from an ensemble of climate models. A future-climate estimate can be derived by the correlation between future and present climate variability and the signal-to-noise ratio obtained from observations and present climate. When a hierarchical statistical framework that links projections of future climate to present-day climate observations is applied to a future northern hemispheric climate projection, a snow-albedo feedback prediction of -1.25%/K to -0.58%/K is found by Bowman et al., (2018). This framework explicitly accounts for model and observational uncertainty. This is driven mainly by the snow-albedo feedback, which is an amplification of temperature due to reduced snow extent as a consequence of anthropogenic CO_2 emissions. This approach can be applied more broadly to constrain future climate projections across the Earth system.

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. One example are the Wallops ozone data, with the total record extending back to the 1960s, are among the most rigorously maintained and accurate in the global network (~100 stations worldwide) as showed by Witte et al., (2019).

Increase in CFC-11 emissions from eastern China

The recovery of the stratospheric ozone layer relies on the continued decline in the atmospheric concentrations of ozone-depleting gases such as chlorofluorocarbons. The atmospheric concentration of trichlorofluoromethane (CFC-11), the second-most abundant chlorofluorocarbon, has declined substantially since the mid-1990s. A recently reported slowdown in the decline of the atmospheric concentration of CFC-11 after 2012, however, suggests that global emissions have increased (Prinn et al., 2018). A concurrent increase in CFC-11 emissions from eastern Asia contributes to the global emission increase, but the location and magnitude of this regional source are unknown. Using high-frequency atmospheric observations from Gosan, South Korea, and Hateruma, Japan, together with global monitoring data and atmospheric chemical transport model simulations, Rigby et al. (2019) investigate regional CFC-11 emissions from eastern Asia. They show that emissions from eastern mainland China are 7.0 ± 3.0 gigagrams per year higher in 2014–2017 than in 2008–2012, and that the increase in emissions arises primarily around the northeastern provinces of Shandong and Hebei. This increase accounts for a substantial fraction (at least 40 to 60%) of the global rise in CFC-11 emissions. No evidence was found for a significant increase in CFC-11 emissions from any other eastern Asian countries or other regions of the world where there are available data for the detection of regional emissions. The attribution of any remaining fraction of the global CFC-11 emission rise to other regions is limited by the sparsity of long-term measurements of sufficient frequency near potentially emissive regions. Several considerations suggest that the increase in CFC-11 emissions from eastern mainland China is likely to be the result of new production and use, which is inconsistent with the Montreal Protocol agreement to phase out global chlorofluorocarbon production by 2010.

Evaluating models of stratospheric composition

To address the questions of how well do a free-running and “nudged” chemistry climate model reproduce global timeseries of upper atmospheric composition (biases, variability, trends), Froidevaux et al. (2019) used Aura Microwave Limb Sounder (MLS) observations of O_3, H_2O, N_2O, HNO_3, and HCl from 2004 to the present to evaluate the depiction of the stratosphere by the Whole Atmosphere Chemistry Climate Model (WACCM), in both free-running and specified-dynamics modes. While the overall model/data match is impressive, a few discrepancies were noted. For example, FR-WACCM generally underestimates the observed H_2O variability. Both models and measurements show an increasing O_3 trend in the southern midlatitudes from 2005 to 2018 that results in an overall positive ozone trend over the longer 1998–2018 period. However, trends for ozone and other species show significant sensitivity to the time period considered, and to variability in the stratospheric Quasi-Biennial Oscillation. Indeed, an underestimate of water vapor variability in global chemistry-climate model simulations (FR-WACCM) implies that the trends predicted by this model for future years would carry smaller error bars than implied by the observed variability. Detailed model/data comparisons such as

Froidevaux et al. (2019) are critical for assessing and refining global atmospheric models, and therefore aid estimation of uncertainties in model predictions of future trends and variability.

Response of stratospheric H_2O, O_3, and the stratospheric circulation to El Niño

An unprecedented disruption of the Quasi-Biennial Oscillation (QBO) occurred at nearly the same time as an extremely strong El Niño event reached its peak in boreal winter 2015/2016. To disentangle the impacts of these two phenomena on stratospheric composition, Diallo et al. (2018) analyzed Aura Microwave Limb Sounder (MLS) measurements of ozone and water vapor using a multiple regression model. They determined that the unusually warm El Niño event substantially increased water vapor (and decreased ozone) in the wintertime tropical lower stratosphere, but the abrupt shift in QBO phase in February 2016 reversed that moistening and significantly dehydrated the global lower stratosphere from early spring to late autumn, with the QBO disruption inducing larger water vapor anomalies than the El Niño event. In a subsequent paper using the same regression model on 12 years (2005–2016) of ozone anomalies from Aura MLS and Lagrangian model simulations, Diallo et al. (2019) found patterns of variations in lower stratospheric ozone that point to ENSO-induced structural changes in the Brewer-Dobson circulation (BDC), the global overturning of mass in the stratosphere. They showed that the "transition" branch (~370–420 K) of the BDC weakens and the "shallow" branch (~420–500 K) strengthens during El Niño, with opposite changes occurring during La Niña. The interplay between ENSO events and QBO phases will be crucial for the distributions of radiatively active trace gases in the future, when climate change is expected to increase El Niño-like conditions and decrease lower stratospheric QBO amplitude. Similarly, ENSO-related structural changes in the stratospheric mean meridional circulation affect the distributions of radiatively active gases in the upper troposphere / lower stratosphere, in turn affecting climate.

Water vapor, clouds, and saturation in the tropical tropopause layer

Schoeberl et al. (2019) used measurements of water vapor, temperature, and relative humidity from NASA's Microwave Limb Sounder (MLS) on Aura in conjunction with aircraft and balloon observations to show that upper tropical tropospheric humidity is close to saturation. This high humidity is the result of the near-continuous upward movement of water vapor from the mid troposphere into the colder upper troposphere that results in extensive cirrus formation. Various model simulations show how this process works and that convective injection of water into the tropical upper troposphere is relatively unimportant. These results shed further light on the processes controlling stratospheric humidity, which have been the subject of debate in the scientific community over the last decade or two.

Attribution of ozone radiative flux bias from satellites in chemistry-climate models

The top-of-atmosphere (TOA) outgoing longwave flux over the 9.6 μm ozone band is a fundamental quantity for understanding chemistry-climate coupling. However, observed TOA fluxes are hard to estimate as they exhibit considerable variability in space and time that depend on the distributions of clouds, ozone (O_3), water vapor (H_2O), air temperature (T_a), and surface temperature (T_s). Benchmarking present day fluxes and quantifying the relative influence of their drivers is the first step for estimating climate feedbacks from ozone radiative forcing and predicting its evolution. Kuai at al., (2019) find that the chemistry-climate models have large differences in TOA flux, attributable to different geophysical variables. The principal culprits are tropical mid and upper tropospheric ozone followed by tropical lower tropospheric H_2O. Most models have TOA flux biases exceeding 100 mWm^{-2} attributable to tropospheric ozone bias. Other models flux biases over 50 mWm^{-2} due to H_2O. On the other hand, T_a radiative bias is negligible in all models (no more than 30 mWm^{-2}). Kuai at al., (2019) report that the AM3 and CMAM models show the lowest TOA flux biases globally but are a result of cancellation of difference processes. Overall, the multi-model ensemble mean bias is -132.9 ± 98 mWm^{-2}, indicating that they are too atmospherically opaque thereby reducing sensitivity of TOA flux to ozone and potentially an underestimate of ozone radiative forcing. Further, the inter-model TOA outgoing longwave radiation difference is well anti-correlated with their ozone band flux bias. This suggests that there is significant radiative compensation in the calculation of model outgoing longwave radiation.

Airborne activities

Programmatic and Earth Venture class Suborbital missions continued to be important contribution of ACFA to supplement current and to 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)

ORACLES completed its third and last field season in September 2018, after the FY2018 GPRA report was written. Since then, important science results were published. For example, ORACLES data revealed that the relationship between cloud droplet number concentration and smoke below cloud is only weakly associated with smoke immediately above cloud at the time of observation. Combining field observations, regional chemistry–climate modeling, and theoretical boundary layer aerosol budget equations, Diamond et al., (2019) show that the history of smoke entrainment has a characteristic mixing timescale on the order of days. Marine boundary layer carbon monoxide concentrations for two case studies suggest that smoke entrainment history drove the observed differences in cloud properties for those days. A Lagrangian framework following the clouds and accounting for the history of smoke entrainment and precipitation is likely necessary for quantitatively studying this system.

The large number of observations acquired during the ORACLES are used systematically to evaluate climate model simulations of smoke and clouds (Mallet et al. 2019). ORACLES is also uniquely positioned to provide new insights into the radiative impact of absorbing aerosols. The sign of the aerosol's radiative effect (warming vs cooling) depend to a first order on the aerosol absorption, expressed by the single-scattering-albedo (SSA) and on the underlying albedo. Obviously, the vertical positioning of clouds and absorbing aerosol layers matter as well. New data from ORACLES in 2016 show that single-scattering-albedo estimates derived from in-situ and remote sensing datasets range from 0.85-0.88 at 500 nm (Pistone et al., 2019 and Cochrane et al., 2019). This is consistent with previous September values reported over the region during the SAFARI campaign. Remote sensing observations above and below cloud and aerosol layers allow to isolate aerosol radiative effect on cloud layers below a lofted aerosol layer. Changes in the thermal heating due to aerosols above clouds can increase or decrease the formation of clouds. As the cloud albedo increases, the aerosol increasingly warms the column. Cochrane et al., (2019) found the transition from a cooling to a warming radiative effect by an aerosol layer found during ORACLES at an underlying albedo of about 0.2 in the mid-visible. Such an albedo corresponds roughly to a cloud cover fraction over the dark ocean of estimated 40%.

We can expect further improvements in our understanding of aerosol radiative effects with improved retrieval algorithms to derive aerosol absorption (Sayer et al. 2019).

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). ATom completed its four flight campaigns in summer 2016, winter 2017, fall 2017, and spring 2018 covering the globe 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. Another example is the mapping of hydroxyl. The hydroxyl radical (OH) is the central oxidant of the lower atmosphere. OH is highly variable in space and time, but current observation-based methods cannot resolve local and regional OH gradients. The robust chemical relationship between OH and formaldehyde (HCHO) (a ubiquitous hydrocarbon oxidation product) is combined with satellite-based HCHO observations from OMI to infer total-column OH throughout the remote troposphere.

Such a dataset from ATom 2016/2017 is discussed in Wolfe et al. (2019) and concurs with previous global average OH estimates while revealing unique features that highlight a dichotomy of regional/seasonal variability and global/annual balance. It offers unique insights on near-global oxidizing capacity. Wolfe et al. (2019) show that OH exhibits significant seasonality within individual hemispheres, but the domain mean concentration is nearly identical for both seasons, and the biseasonal average North/South Hemisphere ratio is 0.89 ± 0.06, consistent with a balance of OH sources and sinks across the remote troposphere. Such fine-scale constraints can help to identify and quantify natural and anthropogenic perturbations and guide efforts to improve simulations of atmospheric composition.

GRL published a paper by Wang S. et al. (2019) using the new comprehensive global data set on atmospheric chemical composition from ATom. Those data show much higher quantities than expected of reactive gases, such as acetaldehyde, in the most remote places in the atmosphere. As much as half of the source of highly reactive free radicals may be missing from current understanding of the effects of pollution on the global atmosphere.

ATom data were also used in a key study by Yu, P., et al., (2019) on in-cloud removal of aerosols by deep convection. They show that the concentrations of primary aerosols including sea salt and black carbon drop by factors of 10 to 10,000 from the surface to the upper troposphere. The default convective transport scheme in the National Science Foundation/Department of Energy Community Earth System Model results in a high bias of 10–1,000 times the measured aerosol mass for black carbon and sea salt in the middle and upper troposphere. A modified transport scheme, which considers aerosol activation from entrained air above the cloud base and aerosol-cloud interaction associated with convection, dramatically improves model agreement with in situ measurements suggesting that deep convection can efficiently remove primary aerosols. Yu, P., et al., (2019) therefore suggest that models that fail to consider secondary activation may overestimate black carbon's radiative forcing by a factor of 2.

A *Nature* paper by Lund et al., (2019) describes the short lifetime of black carbon (BC) inferred from ATom data. They confirm a constraint on the global mean BC lifetime of <5.5 days, shorter than in many current global models, over a broader geographical range than has so far been possible. Large regional differences in the diagnosed lifetime, in particular in the Arctic are found. They also show that only a weak constraint can be placed in the African outflow region over the South Atlantic, indicating inaccurate emission sources or model representation of transport and microphysical processes. While those results confirm that BC lifetime is shorter than predicted by most recent climate models, they also cast doubt on the usability of the concept of a "global-mean BC lifetime" for climate impact studies, or as an indicator of model skill.

Atmospheric Carbon and Transport – America (ACT-America) Mission

ACT-America conducted 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. The following paragraph summarizes selected science highlights published in this reporting period.

Uncertainties in chemical transport models can be significant due to missing or wrong emission estimates and uncertainties in the transport, especially in the case of midlatitude storms. For example, significant differences in global CO_2 flux estimates from satellite XCO_2 are analyzed by Schuh et al., (2019) and attributed to midlatitude storms. Similarly, the CO_2 mole fractions in the planetary boundary layer of the U.S. Midwest caused by biomass burning during summer is found to be biased by such models due to an overestimation of boundary layer wind speeds, and boundary layer height. Feng et al. (2019) also confirms that biological fluxes and atmospheric transport are large contributors to uncertainty in atmospheric CO_2 mole fractions over North America. When averaged over weeks to months, however, uncertainty from both fossil fuel emissions and global boundary conditions exceed the contributions from atmospheric transport. It can be concluded from those papers that both fossil fuel emissions and global boundary conditions using targeted observational strategies will be necessary to improve terrestrial biosphere CO_2 fluxes. This is where ACT-America airborne observations become especially useful to develop, evaluate, and improve model ensembles by observational quantification of CO_2 transport in the midlatitudes. First progress in this direction was achieved by Pal et al., (2019) documenting the greenhouse gas structure of midlatitude cyclones observed across all of the eastern United States during the 2016 summer ACT-America field campaign. Low carbon dioxide (CO_2) mole fractions were observed in the cold sector for every front, in all regions of the United States, with typical CO_2 differences of 10-20 ppm in the boundary layer, and 2-10 ppm in the free troposphere, with differences decreasing with altitude. Methane (CH_4) mole fractions were higher in the cold air in the free troposphere, but boundary layer frontal differences sometimes changed sign. The differences, likely a combination of planetary gradients in greenhouse gas mole fractions and continental fluxes of these gases, will serve as observational metrics used to evaluate atmospheric transport of greenhouse gases by midlatitude storms. More information: https://act-america.larc.nasa.gov

Deriving Information on Surface Conditions from COlumn and VERtically Resolved Observations Relevant to Air Quality (DISCOVER-AQ)

The unique dataset of chemical soundings provided by the DISCOVER-AQ series of air quality field campaigns conducted in 2011-2014 continue to impact scientific understanding across a broad range of topics. Publications over the past year have addressed advances in instrument development, model assessment, and basic understanding of the factors controlling air quality. Instrument development results ranged from an evaluation of small sensor technology for detecting volatile organic compounds that was embedded in the study conducted in Denver, Colorado (Collier-Oxandale et al., 2019) to remote sensing demonstrations for retrieval of aerosol single scattering albedo (Perez-Ramirez et al., 2019) by High Spectral Resolution Lidar and trace gas retrievals of nitrogen dioxide and formaldehyde (Nowlan et al., 2018) from an airborne UV spectrometer. Each of these technologies contribute to the emerging system of observations for air quality that will support NASA's TEMPO (Tropospheric Emissions: Monitoring of Pollution) satellite expected to launch in the next few years. The value of DISCOVER-AQ observations for model assessment includes testing of chemical mechanisms used by the EPA in the Community Multiscale Air Quality (CMAQ) modeling system (Luecken et al., 2019), assessment of emissions from oil and natural gas activities (Abdi-Oskouei et al., 2018), and the assessment of planetary boundary layer height in high-resolution modeling with the Weather Research and Forecasting (WRF) model (Hegarty et al., 2018). A final set of papers evaluate DISCOVER-AQ observations to better understand surface ozone pollution in the coastal environment of Maryland (Mazzuca et al., 2019) and the high

elevation environment of Denver and the northern Front Range of Colorado (Oltmans et al., 2019).
Data access and further information: https://www-air.larc.nasa.gov/missions/discover-aq/discover-aq.html

Korea-United States Air Quality Study (KORUS-AQ)

The international team of investigators analyzing observations from the Korea-United States Air Quality (KORUS-AQ) field study conducted in May-June 2016 published results of ongoing analysis relevant to both understanding the factors driving air quality conditions in South Korea and elucidating the role satellites can play in providing air quality-relevant information. Several papers evaluating the balance between local pollution sources and transboundary sources (largely from China) were published looking at fine particle pollution (Choi et al., 2019), carbon monoxide (Tang et al., 2019), and evidence from geostationary satellite observations of aerosol optical depth (Lee S. et al. 2019). Direct analysis of KORUS-AQ observations yielded insights into local ozone pollution (Sullivan et al., 2019) as well as the components of particle pollution including black carbon (Lamb et al., 2018), organic aerosol (Nault et al., 2019), nitrate aerosol (Romer et al., 2018), and processes controlling new particle growth (Kim and Zhang, 2019). A final set of papers highlighted the potential for satellites to inform top-down estimates of reactive nitrogen emissions (Goldberg et al., 2019), contributions of organic aerosol to fine particle pollution (Liao et al., 2019), multiconstituent satellite data assimilation to assess factors controlling ozone (Miyazaki et al., 2019), and factors governing the relationship between fine particle pollution and aerosol optical depth observations from a geostationary satellite (Lennartson et al., 2018). Additional articles highlighting top-level findings from KORUS-AQ are being submitted to a Special Issue in the journal Elementa for publication later this year. The KORUS-AQ work provides an important basis for future international work on air quality between NASA and Korea's National Institute of Environmental Research (NIER) with the upcoming launches of the TEMPO and GEMS satellites that will provide hourly information on air quality from geostationary orbit over North America and Asia, respectively.
Data access and further information: https://www-air.larc.nasa.gov/missions/korus-aq/ and https://espo.nasa.gov/korus-aq/content/KORUS-AQ

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FY 2019 Annual Performance Indicator	FY16	FY17	FY18	FY19
ES-19-1: 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-19-3: Demonstrate planned progress in improving the capability to predict weather and extreme weather events.

The Weather and Atmospheric Dynamics Focus Area (WAD; 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, transition the scientific understanding and knowledge to operational weather forecast organizations, organize conferences and workshops to assess our current understanding of atmospheric processes, and plan for future research and development activities.

To demonstrate progress in improving the capability to predict weather and extreme weather events, the WAD supports calibration and product generation for weather and atmospheric dynamics related parameters (precipitation, atmospheric temperature and humidity profiles, atmospheric winds, and ocean surface winds). The WAD also invests in characterizing and understanding precipitation processes, atmospheric dynamics, extreme events, convective processes, heuristic atmospheric analysis, numerical weather prediction, and data assimilation improvements as well as strategic development and community engagement. The following sections describe the progress made in the past year.

Characterizing and Understanding Precipitation Processes

Since the end of TRMM mission, GPM has become the main source of precipitation data, and in February 2019 completed 5 years in orbit. 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 (known as IMERG). In 2018, all level-2 microwave and radar products were reprocessed to the latest versions of the algorithms, including a reprocessing of TRMM radar, microwave, and combined products back to 1998 using the GPM algorithms, thus providing a continuous precipitation record across TRMM and GPM. Some of the recent publications related to algorithm development work include Guilloteau et al. (2018), Stocker et al. (2018), Petkovic et al. (2018), Liao and Meneghini (2019), Ringerud et al. (2019), and Tao et al. (2019). Grecu et al. (2018) used airborne observations of cloud microphysical properties from the GPM Olympic Mountain Ground Validation Experiment (OLYMPEX) and Integrated Precipitation and

Hydrology Experiment (IPHEX) field campaigns to develop a nonparametric method to estimate precipitation ice water content from triple-frequency radar measurements. Finlon et al. (2019) used data from the GPM Midlatitude Continental Convective Clouds Experiment (MC3E) field campaign to develop a new approach for characterizing ice particle mass-dimension relationships that may provide benefit for both remote sensing and modeling of precipitation ice.

Data from GPM have produced several scientific accomplishments in the past year. Two studies examined the microphysical characteristics of ice in clouds. Gong et al. (2018) used polarization difference information in GMI's 166 GHz channel to examine the diurnal variation of tropical ice cloud microphysics (related to ice crystal size, shape, and orientation), which had an amplitude of almost 40% over land, but only 6% over oceans. The minimum and maximum of the diurnal cycle of polarization difference led the diurnal cycle of ice cloud mass by ~2 hours, which the authors suggest indicates the importance of ice microphysical processes in the formation and decay of ice clouds. Zeng et al. (2019), using GMI 166 GHz data and CloudSat data, found that optically thick clouds contribute positively to the GMI polarization differences over all latitudes (and vary little with latitude). They suggest that horizontally oriented ice crystals in thick clouds are common from the tropics to high latitudes, whereas findings using CALIPSO data indicate that horizontally oriented ice crystals are rare in optically thin clouds.

Wen et al. (2018) evaluated the performance of six commonly used precipitation products (including the IMERG and TRMM-3B42 products, among others) in several heavy-rain-producing atmospheric river events in California in January and February 2017. They found that IMERG correlated best with rain gauge observations for both the detection and quantification of precipitation, but performed not as well in terms of root-mean-square error or bias. Both satellite and ground-based radar estimates exhibited deficiencies in quantifying rainfall in these events, suggesting that further advancements in measurements is needed.

Cecil and Chronis (2018) developed new polarization corrected temperature (PCT) relationships for GMI's 10-, 19-, 37-, and 89-GHz channels and applied them to identification of intense convection. They suggested that the new formulations of PCT held promise for identifying and investigating intense convection and removing ambiguous signals related to the underlying surface.

Booth et al. (2018), Naud et al. (2018), Wong et al. (2018) examined the rainfall structure of extratropical cyclones. Booth et al. (2018) determined that the precipitation maximum largely occurred prior to the time of maximum dynamical strength of the cyclones and is related to variations in precipitable water over the lifetimes of cyclones. Wong et al. (2018) examined relationships between precipitation and cloud structures and variations in the large-scale moisture flux. Naud et al. (2018) looked at the sensitivity of composite precipitation structures in cyclones to the input data sources.

Several studies used data from the GPM OLYMPEX field campaign to examine the structure and properties of landfalling winter storm systems. Zagrodnik et al. (2018)

examined particle size distributions (PSDs) in storms with orographic enhancement of rainfall, finding that the heaviest rains were characterized by large concentrations of small to medium sized drops with varying concentrations of large drops. McMurdie et al. (2018) looked at terrain enhancement in the ice layer of storms during OLYMPEX using ground-based radar, finding a robust signal of ice enhancement over the windward slopes of the Olympic Mountains. Enhancement was most pronounced in warm sectors of cyclones and in atmospheric rivers under southwesterly flow conditions. Zagrodnik et al. (2019) studied the spatial variability of orographic rainfall properties from airborne radar and ground-based precipitation measurements and found that the degree of modulation was largely controlled by the synoptic environment associated with prefrontal, warm, and postfrontal sectors of midlatitude cyclones.

GPM Ground validation (GV) data and instruments were actively used in a wide range of precipitation studies related to validating space-borne rainfall and snowfall retrievals. Petersen et al. (2019) and Kirstetter et al. (2019) described the GPM program and a range of specific results related to: GV-to-satellite comparisons of the drop size distribution behavior, IMERG validation, and multi-sensor rain rate comparisons analyzed by precipitation type. Seo et al. (2018) provided a comprehensive evaluation of the 2013 Iowa Floods Study (IFloodS) radar-based rainfall products for hydrologic testing. Gatlin et al. (2018) correlated melting layer structure to rain drop-size distribution evolution near the Earth’s surface. Louf et al. (2018) used the GV-developed radar reflectivity Relative Calibration Adjustment and data from both TRMM and GPM to post-calibrate nearly 20 years of Australian radar data from its CPOL facility in Darwin, Australia. Associated CPOL data since GPM launch were subsequently incorporated into the GPM Validation Network (VN) architecture as a tropical maritime site. Wolff et al. (2019) tested new polarimetric radar retrieval techniques and demonstrated improved areal rain maps for Hurricane Harvey.

A significant effort has been made over the last five years to provide estimates of snow water equivalent rate from GPM. For example, Pettersen et al. (2019) provided a composite analysis of snowfall modes using joint data from NASA and the Marquette, Michigan National Weather Service; these data and associated techniques have been incorporated into the GPM VN architecture for continental-scale use. Numerous papers continue to be published using data from the GPM OLYMPEX campaign; e.g., Le and Chandrasekar (2019) provide ground-validation of the surface snowfall algorithm used by GPM’s dual-frequency radar; Zagrodnik et al. (2018) and McMurdie et al. (2018) assessed stratiform precipitation processes, drop size distribution characteristics, and precipitation enhancements both above and below the melting layer, including identifying potential problems in rain estimation along mountain slopes using the GPM DPR.

The majority of radars worldwide do not have the capability to detect light precipitation nor to retrieve drop size and rain rates. Light rain and virga do not contribute the same to water cycle as more intense rain episodes, but these events are at the core of aerosol-cloud interactions and aerosol deposition. Thus, having the ability to detect and retrieve light rain and virga events with an automated network would add valuable data. A study is currently in progress to develop a light precipitation and virga detection algorithm for

NASA MPLNET Lidar Network Measurements. Lolli et al. (2018) examines the utility of using continuous lidar/ceilometer measurements to retrieve rain rates and drop size information with the incorporation of co-located disdrometer data. The disdrometer is an in situ measurement device designed to measure the drop size distribution. They found that the drop size distribution can be reconstructed from the Lidar data between ground and cloud base. This will enable an assessment of light precipitation inter-annual intensity variability from long-term (>15 years) MPLNET stations, especially in polluted regions, to quantifying for the first time the aerosol indirect effects on drizzle reduction/suppression.

Atmospheric Dynamics

Improving the predictability of weather and extreme events as well as understanding climate change and the corresponding cascade of societal impacts are key NASA strategic goals. Modern microwave and hyper-spectral infrared weather sounders are measuring the top of atmosphere radiance at unprecedented accuracy and precision and are a direct and diagnostic measure of climate change. These radiances can be inverted to retrieve relatively high vertical resolution soundings of temperature and water vapor, cloud parameters, and atmospheric trace gas concentrations. The weather, air quality, and climate communities require accurate and unbiased atmospheric thermodynamic and composition products with global spatial coverage to generate stable long-term climate data sets to study the Earth's seasonal and inter-annual variability, climate processes and changes in composition. The NASA Sounding Discipline provides these communities with state-of-the-art algorithms and unique data products.

NASA continues to make complete atmospheric profile measurements, including observations of temperature and moisture from the surface to at least lower stratosphere, 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. AIRS is expected to continue operating throughout the Aqua mission.

For Suomi-NPP and JPSS-1, NASA/GESDISC is processing radiance (level-1) products from the Cross-Track Infrared Sounder (CrIS) and Advanced Technology Microwave Sounder (ATMS, 22 channels) using the most recent calibration algorithms (https://disc.gsfc.nasa.gov/information/glossary?title=CrIMSS%20Cross-track%20Infrared%20Sounder%20(CrIS)%20and%20Advanced%20Technology%20Microwave%20Sounder%20(ATMS)%20instrumentation). A state-of-the-art retrieval algorithm was implemented at the NASA Sounder SIPS to utilize radiances from both suites, AIRS/AMSU from Aqua and CrIS/ATMS from Suomi-NPP and JPSS-1. This algorithm builds on advances made by the AIRS Science Team to establish continuity in retrieved sounding parameters between two different instrument suites for the first time. With its innovative characterization of retrieval quality and uncertainty, it makes meaningful contributions to climate data science and the understanding of climate processes at large space-time (Smith and Barnet 2019). Moreover, its multi-instrument approach extends the value of AIRS well beyond its operational lifetime by enabling a multi-decadal data record that will go into production for Aqua, Suomi-NPP and JPSS-1 at NASA/GESDISC in the fall of 2019.

In an attempt to create ling-term climate data record, Motteler and Strow (2019) reported the different characteristics of AIRS and CrIS measurements. These instruments have broadly similar spatial sampling, spectral resolution, and band spans. However the spectral response functions differ in detail, leading to significant differences in observed spectra. To address this, they translate channel radiances from one sounder to another, including simulation of the response functions of the translation target. Such translations are used from AIRS to CrIS and IASI to CrIS, and have implemented and tested IASI to AIRS and CrIS to AIRS translations as well. Their translation from AIRS to CrIS has some novel features. AIRS is a grating spectrometer with a distinct response function for each channel, whereas CrIS is a Michaelson interferometer with a sinc response function after calibration and corrections. They use the detailed knowledge of the AIRS spectral response functions to deconvolve AIRS channel radiances to a resolution enhanced intermediate representation. This is then reconvolved to CrIS or other instrument specifications. The resulting translation is shown to be more accurate than interpolation or regression.

Using the AIRS radiance data, Reale et al. (2018) performed a study to improve the impact of assimilating AIRS radiances, particularly in partially cloudy environments, in the GEOS global data assimilation and forecast system. Specifically the impact of a simple adaptive thinning methodology is evaluated through a combination of observing system experiments (OSEs) and adjoint methodologies. The study found the methodology improves global forecast skill and tropical cyclone representation is substantially improved. The work will continue to take this methodology in assimilation of AIRS radiances and apply to CrIS radiances to improve both hurricane intensity and track forecasting in an operational setting.

Beside the temperature and moisture profiles, in a series of two papers, Tucker et al. (2018) and Baidar et al. (2018) presented the motivation, instrument design, implementation, and initial validation testing of a Doppler wind lidar (DWL) based on direct-detection of Doppler shift from aerosols and constituent molecules in the air. The Optical Autocovariance Wind Lidar (OAWL) is currently two-line-of-sight and dual-wavelength (355 and 532 nm) and is validated with from autumn 2011 and spring 2016 test flights. For the latter test flight, the instrument is further developed to demonstrate the spaceborne mission concept on a WB-57 platform (Baidar et al. 2018). The Atmospheric Transport, Hurricanes, and Extratropical Numerical Weather Prediction with the Optical Autocovariance Wind Lidar (ATHENA-OAWL) showed excellent agreement with dropsondes ($R2 > 0.9$) and may be used for improving numerical weather prediction especially for hurricanes and atmospheric transports.

Flight of an Improved Lidar Wind Instrument
The NASA LaRC Doppler Aerosol WiNd Lidar (DAWN), High Altitude Lidar Observatory (HALO), and Yankee Environmental Systems (YES) dropsonde systems flew aboard the NASA DC-8 for 46 hours from 17-30 April 2019. These April 2019

NASA Aeolus Cal/Val Test Flight Campaign collected some of the first-ever simultaneous airborne lidar wind, water vapor and aerosol profile data, using the DAWN and HALO instruments. DAWN and HALO collected wind, aerosol, cloud, and water vapor profiles throughout the Eastern Pacific Ocean and Southwest U.S. The objectives of this flight campaign were to: (1) Demonstrate DAWN and HALO instrument performance across a wide variety of conditions, and (2) Perform initial validation of the ESA ADM Aeolus Level 2B wind and Level 2A aerosol profiles. Five Aeolus underflights were conducted. Winds ranging from 0 to ~60 m/s were observed along the Aeolus ALADIN lidar track. A total of 31 YES dropsondes were released along the Aeolus track, and 33 additional at other times during flight to validate Aeolus/DAWN winds and HALO water vapor profiles. Initial comparisons between DAWN, dropsondes, and HALO and Aeolus look reasonable though all instruments still require calibration activities. These flights were in preparation for a joint NASA-ESA Aeolus Cal/Val Field Campaign being planned for July and August of 2020 to be based out of Capo Verde.

Study of Extreme Events

Precipitation extremes
In their recent paper, Adhikari and Liu (2019) examined the geographical distribution of thundersnow events using GPM data and Worldwide Lightning Location Network data. They identified 443 events in four years, most of which were found of mountainous regions such as the Himalayas, Tibet, the Andes, and the Zagros Mountain regions. Non-inductive charging processes were inferred to be important in these events.

Lightning measurements
The Lightning Instrument Package (LIP) represents a unique airborne research capability for conducting detailed electrical investigations of thunderstorms and lightning for science and applications research. The current LIP airborne architecture utilizes 6 to 8 electric field sensors per aircraft installation to measure the electric field. LIP measures the full vector components of the atmospheric electric field over a wide dynamic range extending from fair weather electric fields (i.e., a few V m^{-1}) to large thunderstorm fields (i.e., tens of kV m^{-1}), providing detailed information about the electric structure within and around the observed storms. A conductivity probe also is included in some airborne LIP configurations. Combining the conductivity with the electric field provides a direct measure of the storm electric current contribution to the global electric circuit. A recent paper by Østgaard et al. (2019) reports LIP flew during a 2017 joint NASA/NOAA high altitude ER-2 airborne field campaign to help calibrate and validate observations from the new Geostationary Lightning Mapper on NOAA's GOES-16 weather satellite. Immediately following the GOES campaign, LIP, now moved to a Citation aircraft, participated in an initial proof-of-concept, day-of-launch decision demonstration at Kennedy Space Center on how near real time electric field observations from LIP under certain weather conditions could allow a launch to proceed that is now prevented due to weather launch rules.

A space-qualified Lightning Imaging Sensor (LIS), built as the flight spare for the Tropical Rainfall Measuring Mission (TRMM), is operating on the International Space

Station (ISS), extending the 17-year TRMM LIS record of tropical lightning measurements and expanding that coverage to higher latitudes missed by the previous mission. The ISS LIS continues the science focus to better understand the connections between lightning and subsequent severe weather events, key to improving weather predictions and saving lives and property here in the United States and around the world. The ISS LIS measurements also to help calibrate/validate observations from the new Geostationary Lightning Mapper (GLM) sensors that are on NOAA's two newest weather satellites GOES-16 and 17. Erdmann et al. (2019) describe comparisons of LIS to ground-based lighting detection systems in Europe, as the Europeans seek to develop proxy data in advance of the Meteosat Third Generation-Lightning Imager (MTG-LI), slated for launch in late 2021. Two other especially unique contributions from LIS being on the ISS platform are providing real-time lightning data for operational forecasting and warning applications over data sparse regions such as the oceans, and simultaneous and complementary observations with the recently launched European Space Agency's Atmosphere-Space Interaction Monitor (ASIM) that is exploring connections between thunderstorms and lightning with terrestrial gamma-ray flashes (TGFs). In June 2019, the LIS program successfully completed an End of Prime Mission review and was granted a one-year operations extension. In late summer 2019, the LIS dataset transitioned from Provisional to Validated. Validated means that the products are at a high-quality level deemed suitable for systematic science studies. The early science results using the Provisional data already showed excellent agreement with the lightning statistics and climatology from the prior observations of its TRMM LIS and Optical Transient Detector predecessors.

Products to Support Major Hurricanes

The hurricane season of 2018 brought several significant storms to the Atlantic basin including two major hurricanes and four tropical cyclones making landfall in the U.S., including Alberto, Florence, Gordon, and Michael. Hurricane Florence made landfall in North Carolina as a Category 1 storm, but the storm slowed down with a good portion of its circulation over water, setting the stage for major flooding over the Carolinas that was determined by IMERG products. Flood maps from Sentinel-1 and nighttime imagery from the Suomi-NPP VIIRS instrument highlighted the damage and impacts left in the wake of the storm. Hurricane Michael made landfall as a Category 5 hurricane with sustained winds of 160 mph (260 km/h), becoming the strongest storm of the season and also the third-strongest landfalling hurricane in the U.S. on record in terms of central pressure. GPM IMERG recorded rainfall totals of 10 inches (254 mm) along much of Michael's track and peak values over 20 inches (512 mm) off the Yucatan peninsula. GPM's Dual-frequency Precipitation Radar (DPR) observed intense rainfall in the center of Tropical Storm Isaac, measuring rainfall rates of over 140 mm/hour and echo-top heights reaching 16.2 km (10 miles) in the area of strongest convection. GPM's microwave data are being implemented into the National Weather Service's (NWS) Advanced Weather Interactive Processing System (AWIPS) that enables forecasters throughout the U.S. to make weather predictions and provide rapid and highly reliable weather warnings and advisories for tropical cyclones.

The 2019 hurricane season had an active start, including two hurricanes and two tropical storms that made landfall on the U.S. Before making landfall on the U.S., Hurricane Dorian tied the Labor Day hurricane of 1935 for strongest wind speeds ever recorded in the Atlantic Basin at 185 mph and was the worst natural disaster to strike the Bahamas. Multispectral Red-Green-Blue (RGB) composite imagery from GPM passive microwave (37 and 89 GHz) sensors monitored the evolution of the structure of Dorian (https://nasasport.wordpress.com/2019/09/04/viewing-an-eyewall-replacement-cycle-and-the-structural-evolution-of-hurricane-dorian-using-nasas-gpm-constellation/).

CYGNSS

CYGNSS calibration and retrieval algorithm improvements in FY18 resulted in a significant reduction in the uncertainty of its high wind speed measurements, from 17% RMS error with the v2.0 high wind data product to 11% with v2.1 (Ruf et al. 2019). The improved performance has supported ongoing investigations to increase hurricane forecast skill by assimilation of CYGNSS observations into numerical weather prediction models (Annane et al. 2018). One such effort has demonstrated that knowledge of surface wind speed and associated latent heat flux in the inner core of the storm, which is not possible without the ability to penetrate through heavy precipitation, allows for azimuthally asymmetric wind distributions aloft to be forecast significantly better (Cui et al 2019). A second effort addresses the situational awareness of tropical cyclones by demonstrating that the use of CYGNSS wind observations in and near their inner core allows for improved determination of the storm center location (Mayers and Ruf 2019).

CYGNSS also provides valuable insight into the relationships between wind-driven surface fluxes and general tropical oceanic convection. Specifically, its observations can detect convective wind features over a variety of spatiotemporal scales, from Westerly Wind Bursts associated with the Madden-Julian Oscillation, to downdraft-induced gust fronts from mesoscale convective systems (MCSs) (Hoover et al. 2018). Significant oceanic MCSs have been identified and collocated with CYGNSS observations under precipitation. Examination of changes in surface winds along the CYGNSS tracks reveal clear evidence of the signatures of convectively generated gust fronts.

Understanding Convective Processes

Above-Anvil Cirrus Plume

In a collaboration between LaRC and the University of Oklahoma, Bedka et al. (2018) identified a pattern present within GOES imagery of thunderstorm cloud tops that indicates an especially severe storm. Updrafts that penetrate into the stratosphere inject ice crystals that form a plume of cirrus clouds several kilometers above the layer of thunderstorm outflow, commonly referred to as anvil clouds. These so-called "above anvil cirrus plumes" are anomalously warm and have unique texture that can be easily identified by a forecaster given minimal training. Storms that generate plumes were analyzed using GOES, weather radar, and lightning observations, coupled with spotter reports of hail, wind, and tornadoes that define exactly when severe weather occurred on the ground. This analysis revealed that, on average, storms that produce above anvil plumes are an especially intense subset of deep convection, featuring the highest cloud tops, strongest updrafts, most lightning, and a high frequency of severe weather. It was found that plume-producing storms generated 14 times more severe weather reports than storm cells without plumes. 73% of the catastrophic severe weather events, 2+ inch diameter hail, 65+ knot wind, or EF-2+ tornadoes, were generated by plume-producing storms. Several briefings to National Weather Service forecasters have recently been given to inform them of this new research and how it can help in the severe storm warning process.

An Aviation Hazard Identification

GOES-R series imagery was also combined with in-situ observations of cloud ice water content to better understand processes contributing to aircraft engine icing. Recent studies (Yost et al., 2018, Bedka et al., 2019) have found that high mass concentrations of ice particles within deep convective storm anvils can adversely impact aircraft engine and air probe (e.g. pitot tube and air temperature) performance. Onboard weather radar reflectivity in these regions suggests that they are safe for aircraft penetration, yet high ice water content (HIWC) is still encountered. A flight campaign in August 2018 with the NASA DC-8 aircraft flew throughout convective storms to identify where HIWC was present. NASA LaRC researchers found that optically thick clouds with tops near to or above the tropopause in close proximity (≤ 40 km) to convective updrafts were most likely to contain HIWC. An automated GOES-based HIWC detection product was developed and validated based on this and other recent international field campaign data. In collaboration with NASA MSFC SPoRT scientists, this product was provided in near real-time to NOAA aviation weather forecasters in Houston, Fort Worth, and Memphis for evaluation in an operational forecasting environment. The product was very well-received, and example feedback from a meteorologist in Houston is as followed: “The HIWC product showed the enormity of the hazards at onset and throughout this event...HIWC provides hazard information in near-real time at a spatial and temporal resolution that is not replicated in any other available product.”

Convective Process Experiment (CPEX)

Analyses and diagnoses of the CPEX field campaign held in 2017 are ongoing. The campaign provided new insights into convective processes with the use of the DAWN wind lidar and the APR-2 radar with other instrumentation onboard the DC-8 (https://airbornescience.nasa.gov/content/Convective_Processes_Experiment_CPEX). Notably, the two instruments are being used together to investigate upscale growth and the precipitation inside convection (APR-2) along with the winds (DAWN) inside and outside the precipitation. DAWN lidar was also able to penetrate to near ocean boundary layers for investigations of ocean wave sea salt spray. Tropical Storm Cindy was a focus of research wherein science team members found unexpected pockets of warm dry air about 2.5 km in altitude just prior to intensification. Using polarization corrected temperatures (PCTs) associated with GPM GMI overpasses broken into an ice PCT (using 166 GHz) and a liquid PCT (using 85 GHz) allowed partitioning of CPEX observations into categories of ice, mixed phase, and liquid particles within the cloud.

Mesoscale Convective Systems (MCS)

Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ), a joint venture led by NOAA and NASA, provides comprehensive observations to investigate the impact on air quality and climate from wildfires and agricultural fires across the continental United States (https://www.esrl.noaa.gov/csd/projects/firex-aq/). A NASA ER-2 high-altitude research aircraft, one component of FIREX-AQ, is the intermediate step between in-situ and satellite observations and will acquire replicate data collected by orbiting satellites at the same time that other aircraft and ground sensors are sampling in smoke plumes. The FIREX-AQ campaign was explained in greater depth by Atmospheric Composition Focus Area.

Convective clouds produce a significant proportion of the global precipitation and play an important role in the energy and water cycles. From CloudSat and CALIPSO observations, Jiang et al. (2018) found that aerosols can inhibit or invigorate convection, depending on aerosol type and concentration. On average, smoke tends to suppress convection and results in lower cloud altitudes than clean clouds. Polluted continental aerosol tends to invigorate convection and promote higher cloud altitudes. The dust aerosol effects are regionally dependent and their signs differ from place to place in South America, Central Africa and Southeast Asia. Moreover, Jiang et al. (2018) found as well that the aerosol inhibition or invigoration effects do not vary monotonically with aerosol optical depth and the variations depend strongly on aerosol type. Our observational findings indicate that aerosol type is one of the key factors in determining the aerosol effects on convective clouds.

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 and regional 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. Accurate representation of cloud-precipitation-radiation interactions is critical to assimilation of GMI all-sky radiances in global and regional models. Sieron et al. (2018) examined the impact of the representation of ice particles in the Community Radiative Transfer Model (CRTM), finding that simulated brightness temperatures better matched observations when non-spherical particles were used in the CRTM. Furthermore, sector snowflakes yielded better brightness temperatures than other particle habits (bullets, plates, rosettes, dendrites), and simulation results suggest that the model generally overproduces total snow and graupel content.

In another study (Pu et. al., 2019), the impact of assimilating Global Precipitation Measurement (GPM) Microwave Imager (GMI) clear-sky radiance on the track and intensity forecasts of two Atlantic hurricanes during the 2015 and 2016 hurricane seasons is assessed using the Hurricane Weather Research and Forecasting (HWRF) Model. Forecast results show that assimilating GMI clear-sky radiance has positive impacts on both track and intensity forecasts, with the extent depending on the phase of hurricane evolution. Forecast verifications against dropsonde soundings and reanalysis data show that assimilating GMI clear-sky radiance, when it does not overlap with overpasses of other microwave sounders, can improve forecasts of both thermodynamic (e.g., temperature and specific humidity) and dynamic variables (geopotential height and wind field), which in turn lead to better track forecasts and a more realistic hurricane inner-core structure.

Atmospheric models, and parameterizations of clouds and precipitation within the models, can be verified with global precipitation products. Tapiador et al. (2019) discusses the usefulness of precipitation for model verification and validation and the important role of highly precise satellite measurements such as those from the GPM Core satellite. Precipitation is viewed as a tough challenge for models to get right, but is a test spurred by societal demand for improved precipitation forecasts. While the precipitation estimates are critical for improving models, the authors also highlight the need to continually improve the precipitation measurements as well.

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 a major 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.

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 (v2.3.1) has been developed and released, 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 coordinating the migration of observation operators into the Unified Forward Operator (UFO) for a variety of satellite instruments.
- Impact of Observing System: the international inter-comparison study of Forecast Sensitivity Observation Impact (FSOI) has been extended to a near-real-time monitoring and diagnostics capability for the GMAO and Naval Research Laboratory (NRL) systems.
- Joint Effort for Data assimilation Integration (JEDI): 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 second and third 'JEDI Academy' were held in College Park and Boulder respectively to train early adopters about the software, object-oriented programing and new work practices.

- Sea-ice, Ocean, Coupled Assimilation: development of a data assimilation prototype for ocean and sea-ice within the JEDI infrastructure, resulting in realistic analysis increments in 30-day cycling experiments. An extended suite of observations, including retrievals from satellite data, are now included in the JEDI system capability.

As part of the JCSDA external research activities, a NASA funded project (Oyola et. al., 2019) investigated the impact of mineral dust and thin cirrus contamination on hyperspectral data assimilation for operational weather forecasting through the synergistic use of AIRS, CrIS, CALIOP, MODIS and MISR data. The study coupled the Navy's global weather model, NAVGEM, with its aerosol mass transport model, NAAPS, to apply dust presence to the forward-modeling phase of CrIS and IASI hyperspectral IR sounder radiance data assimilation. Framework to call CRTM with NAAPS aerosol shows neutral impact at present, but has proven robust. Results from multi-month system evaluation over two separate years (2017 and 2018) evaluated. Improvements to the NAAPS/CRTM interface will be a main focus going forward.

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. 2018; Mishra et al. 2018). The team is working to develop an Alaska-based scheme to understand soil moisture variability during the wildfire season to aid the Alaska Fire Service and their partners.

- SPoRT has contributed to the transition of Geostationary Lightning Mapper (GLM) observations from the GOES-16 and GOES-17 weather satellite to operational forecasters at the NOAA National Weather Service (NWS) and emergency management staff at NASA MSFC (Stano et al. 2019). The team continues to work collaboratively with NOAA and other operational users to develop common web and software displays through a NOAA Joint Technology Transfer Initiative (JTTI) to incorporate GLM data into day-to-day operations, as well as, the development of new products to diagnose the intensity of convection, identify lightning-initiated wildfires (Schultz et al. 2019), and provide lightning risk metrics for lightning safety applications (e.g., Stano et al. 2019).
- With the transition of Multispectral imagery from the Advanced Baseline Imager (ABI) from the new GOES-16 and now -17 weather satellites 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 (Berndt et al. 2018). In addition SPoRT contributed to the national NWS training effort by creating training material on GOES-16/17 multispectral composites that are available to NWS forecasters in the NOAA Learning Management System and online through VISIT (http://rammb.cira.colostate.edu/training/visit/). Part of the transition and training effort included formal assessments of the Dust and Night-time Microphysics imagery.
- SPoRT has completed transition of Multispectral imagery from polar-orbiting satellites (NASA Terra/Aqua MODIS, NASA/NOAA S-NPP/NOAA-20 VIIRS) to operational forecasters at the NOAA National Weather Service (NWS) in Alaska Region. SPoRT developed a capability to provide high-quality limb-corrected and inter-calibrated imagery and process it in operational NWS systems. SPoRT transitioned the scientific capability to NOAA NWS and will be able to phase out processing and providing multispectral imagery to Alaska Region partners. (Berndt et al. 2018). The transition of capabilities includes real-time processing of the 3.9 reflectance which is an important component in the Day-time Microphysics imagery. Forecasters have integrated the multispectral imagery in operations as exemplified in Lawson and Fuell (2019).
- SPoRT has completed the operational transition S-NPP and NOAA-20 CrIS/ATMS gridded soundings to NOAA NWS. SPoRT has been part of a multi-organizational effort to develop the capability to grid and view satellite soundings as plan view displays in the NOAA NWS operational display system. The capability was released to the NOAA NWS during FY19. The capability supports

applications such as the Cold Air Aloft aviation hazard (Weaver et al. 2019), diagnosing the pre-convective environment, assessment of hurricane and mid-latitude cyclone development and intensity changes (Berndt and Folmer 2018), and fire weather conditions.

- SPoRT has engaged with a series of 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.
- ESI was also used in the wildfire community. The team examined ESI in Alaska to understand how ESI provides different information on vegetation health at high latitudes as compared to their traditional use of the normalized difference vegetation index (NDVI). Furthermore, these ESI measurements aided decision support in response to the ongoing Camp fire this past November (2018). ESI showed that there was a delay to the rainy season, and highlighted where the vegetation stress near Paradise, CA was most exacerbated and where they might have to focus their efforts as the fire spread.

Strategic Development and Community Engagement

GPM's suite of precipitation products continues to inform scientific studies and benefit societal application activities. These include, but are not limited to, numerical weather prediction, disaster preparation and response, water resource management, drought monitoring, famine early warning, disease tracking, energy infrastructure and management, animal migration, and global climate modeling. Many of these applications require near real-time data for easy ingestion and analysis. Near real-time GPM precipitation data continues to support local, regional, and global assessments of natural disaster events, including the Global Flood Monitoring System (http://flood.umd.edu) and Landslide Hazard Assessment for Situational Awareness (LHASA) model (https://pmm.nasa.gov/applications/global-landslide-model), as well as to inform disaster communications by the Joint Typhoon Warning Center, Pacific Disaster Center, Global Disaster Alert and Coordination System, and the Extreme Rainfall Detection System. GPM rainfall estimates are further being applied by commercial companies to understand and quantify how weather impacts alternative energy resources including assessing the impact of rainfall on wind turbine blades and assessing the hydrological budget to characterize potential opportunities for hydropower plant construction. Lastly, GPM rainfall estimates continue to be assimilated into computational models of water- and vector-borne disease transmission to improve short-term projections of epidemics in near real time (Pasetto et al. 2018).

The GPM Applications Team has also expanded its reach to both understand and quantify how GPM data products are applied within different user communities for decision making as well as promote examples of how GPM data can benefit society. Mechanisms include engaging user communities through workshops (Weather and Air Quality Workshop, July 2019) and interviews, promoting the use of GPM data with outreach materials (one-pagers, weekly highlights), and improving data access and visualization of core GPM products through platforms like ArcGIS Online. The team has also developed a portfolio of over 4850 unique GPM users to highlight the types of application areas and GPM products that are most relevant to the user community and locations around the world.

Planetary Boundary Layer Research Planning

The recent National Academies' Earth Science Decadal Survey recommended the PBL as a targeted observable priority for incubation studies of future satellite observations. At this stage, it is considered critical for the PBL science community to present and discuss the most recent technology and science developments in the context of space-based observations of the PBL. Because of this, a PBL Workshop was coordinated and held contiguous with the normal fall NASA Sounder Science Team Meeting (STM). The combined meeting was held during the week of October 1-5, 2018, in Greenbelt, MD. The PBL Workshop agenda included presentations that covered a variety of model processes, and space-based and in situ observational systems. The Sounder STM sessions included Weather and Climate, Atmospheric Composition, Applications, Retrievals, Validation, and Calibration. The AIRS STM organized in April 2019 included similar sessions to the ones mentioned above. In addition, several presentations at this meeting were also focused on aspects of the PBL. In addition, a session on 'Observing the PBL from Space' was organized as part of the American Meteorological Society (AMS) annual meeting in Phoenix, Arizona, in January 2019. During this session, presentations focused (i) on studies that utilize space-based observations of the PBL in the context of weather, air quality and climate; and (ii) on potential future PBL observational systems from space.

The planetary boundary layer (PBL) is at the heart of a number of fundamental atmospheric science challenges: (i) cloud-climate feedback (how clouds will respond and impact climate with increased greenhouse gas concentration) is essentially about the interactions between a highly turbulent flow with water phase transitions and radiation, often occurring in the PBL; (ii) the extreme weather and climate change problem is essentially about how deep moist convection, with its roots in the PBL, will respond to a warmer world; (iii) the exchanges of energy, water and carbon between the atmosphere, ocean, land, and ice are mediated by turbulent fluxes in the PBL; (iv) the depth and mixing of PBL air significantly influences air quality and human health.

Weather forecasts are routinely produced by numerical weather prediction (NWP) centers around the world and the PBL plays a critical role in key weather events. The recent NASA Weather Focus Area community workshop report highlighted the importance of the PBL for weather, and some key unsolved questions. For example, how does moist convection interact with the PBL and the surface? What are the fundamental mechanisms controlling ABL clouds?

17th JCSDA Technical Review & Science Workshop on Satellite Data Assimilation, May 29-31, 2019

Hosted by NASA Headquarters, 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. This year, the focus was on the development of the Joint Efforts for Data assimilation Integration (JEDI) which will become the core data assimilation system used by multi-agencies including NASA, NOAA, Air Force, and Navy.

Working Group on Space-based Lidar Winds Meeting, July 10-11, 2019

Nearly 50 scientists and technologists representing NASA, NOAA, private industry, academia, and ESA attended the meeting. The agenda included updates from the 2018 Earth Science and Applications from Space Decadal Survey, wherein 3D Atmospheric Wind observations were placed into the Explorer category meaning that these observations will be competed against 6 other important observations identified by the DS starting in the 2023 timeframe; NOAA's efforts related to the NOAA Satellite Observing Systems Architecture (NSOSA) study; and the status of the European Space Agency's Aeolus lidar wind mission (launched August 2018) was reported and the data is still being calibrated while the mission has also recently switched to the second laser onboard. In addition, current US activities associated with space-based wind lidar were covered. Presentations on passive wind measurement techniques based on atmospheric motion vectors (AMVs) led into discussion on potential synergisms between lidar and AMV observations for future missions. The relationships between atmospheric winds and the planetary boundary layer were a focus of the meeting discussions, Action items identified for attention prior to the next meeting included further investigation of combined lidar/AMV wind observation concepts, assessing NOAA versus NASA needs for wind observations, and identifying user and application communities in need of wind data.

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FY 2019 Annual Performance Indicator	FY16	FY17	FY18	FY19
ES-19-3: Demonstrate planned progress in improving the capability to predict weather and extreme weather events.	Green	Green	Green	Green

Annual Performance Indicator ES-19-6: 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 simulation 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. Unique to this report, the Second State of the Carbon Cycle Report (USGCRP 2018) was released with relevance to all topics for Carbon Cycle and Ecosystems, and in particular, for coastal and freshwater ecosystems and biogeochemistry. Future capabilities include (1) DELTA-X, an EVS-3 selected in late 2018, that will use field and airborne observations to develop a modeling framework of soil accretion, vegetation growth, and soil erosion in the Mississippi Delta that can then be extended to other delta regions and (2) an EVI-5 selected in 2019, the Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR) that will make hyperspectral observations of coastal waters centered on the Gulf of Mexico and the Amazon River plume. Both selections will help improve capabilities towards ecosystem sustainability, improve resource management, and enhance economic activity. Selected research results and other accomplishments of the 2019 fiscal year are highlighted below.

1. Mapping and Modeling Land Cover and Land Use Change (LCLUC) in Southern and Southeast Asia, Africa and Europe

Trends in fire intensity and frequency as well as changes in vegetation types in Southern/Southeast Asia (S/SEA) were examined by Vadrevu et. al., (2019) with the Moderate Resolution Imaging Spectroradiometer (MODIS) from 2003–2017 and Visible Infrared Imaging Radiometer Suite (VIIRS) from 2012–2016 at the country level. MODIS data suggested that India, Pakistan, and Indonesia show statistically significant increasing trends in number of fires. Fire frequencies in cropland residual burning was equal to forests, with human ignition as the primary cause (agricultural fires spreading from farms to forests, abandoned cooking fires, carelessness due to smokers, firewood collectors). Fire trends from VIIRS were not significant due to shorter temporal period available. For S/SEA, precipitation showed a stronger correlation to number of fires relative to temperature. Results on fire statistics including spatial geography, variations, frequencies, anomalies, trends, and climate drivers can be useful for fire management in S/SEA countries. Section 4, below (Global Vegetation Dynamics and Trends), provides insight into changing productivity and agricultural extent in India (Chen et al., 2019). It is important to note that these two studies (Vadrevu et al., 2019 and Chen et al., 2019) were independent and increasing fire trends in the Vadrevu et al., (2019) paper are not necessarily conflicted with the Chen et al., (2019) analysis. That is, increasing fires over the period examined by Vadrevu et al., (2019) over the entire subcontinent of India does not exclude possibility of increasing fires with changes in agricultural extent as described by Chen et al., (2019).

Zhang et al., (2018) compared Sentinel-2A and Landsat-8 data for approximately 10° × 10° of southern Africa for two summer (December and January) and in two winter (June and July) months of 2016. Results are being used to improve the consistency between Sentinel-2A MSI and Landsat-8 OLI data.

Manakos et al., (2018) discussed global partnerships in the Global Observations of Forest Cover—Global Observations of Land Cover Dynamics (GOFC-GOLD), South Central and Eastern European Regional Information Network (SCERIN). The main objective was to evaluate the accuracy of commonly used Global and Continental Land Cover Products (GCLCs) at selected representative study areas in the SCERIN geographic area, characterized by extreme diversity of landscapes and environmental conditions, heavily affected by anthropogenic impacts with similar major socio-economic drivers. The study revealed overall high credibility and validity of the GCLC products at local scale, a result, which shows expected benefit even for local/regional applications. Class dependent land cover types were identified in different landscapes and will be useful to guide users in local studies.

2. Observing Carbon Stocks and Fluxes for Stakeholder Communities

The NASA Carbon Monitoring System (CMS) is a forward-looking initiative designed to characterize, quantify and predict the evolution of global carbon sources, sinks, and fluxes through improved monitoring of terrestrial and aquatic carbon stocks and fluxes. Accurate, estimation of forest carbon stocks (i.e., aboveground biomass) at high-resolution has remained a challenge. However, commercial off-the-shelf measurement capabilities such as airborne LiDAR data have been effectively leveraged to meet this challenge. For example, Huang et al. (2019) mapped forest aboveground biomass at high spatial resolution over three states in the USA (Maryland, Pennsylvania and Delaware with a total area of 157,865 km^2) by linking airborne lidar and field data with machine learning algorithms. The LiDAR derived biomass maps provided an estimate of total aboveground biomass (~680 Tg C) over this region. These data were integrated into an ecological modelling framework by Hurtt et al. (2019) to estimate the carbon sequestration potential across the state of Maryland. They estimated the forest aboveground carbon sequestration potential of Maryland to be 204.1 Tg C, nearly double the current stock in the state. The time needed to reach this potential was estimated to be 228 years, with 50% of the gap being realized in 80 years. These results imply a large statewide potential for future carbon sequestration from afforestation and reforestation activities in Maryland.

Local, high-resolution lidar-derived biomass maps such as the one described above can provide a valuable bottom-up reference to improve the analysis and interpretation of large-scale above ground biomass mapping efforts from newly launched and upcoming

Earth Observation missions that collect data sensitive to forest structure and aboveground biomass (e.g., GEDI, ICESat-2, NISAR, etc.). These new missions will facilitate the development of novel global forest biomass products in the coming decade. However, without consistent validation, these biomass products may not effectively support various policy, management and science applications. Duncanson et al., (2019) outline the wide range of anticipated user requirements for product accuracy assessment and provide recommendations for the validation of biomass products that will ultimately be leveraged in the biomass land product validation protocol being develop by the Committee on Earth Observing Satellites (CEOS).

Recent advances in satellite remote sensing of solar-induced fluorescence (SIF) are promising for estimating gross primary production (GPP), with emerging capability in space-based methodologies and diverse application prospects (Mohammed et al., 2019). However, the empirical link between GPP and SIF has mostly been observed at coarse spatial and temporal scales and lacks a direct mechanistic explanation. A recent study by Mangey et al. (2019) use a novel tower-based SIF sensor to track and understand the seasonality of photosynthesis at a sub-alpine conifer forest in Colorado. They found that the relationship between SIF and GPP was highly linear year-round at daily, weekly, and monthly time scales, and the seasonal patterns of both were very similar, indicating SIF is a powerful proxy for GPP and provides information on plant light use efficiency. SIF measurements from the tower-based sensor were also consistent with satellite SIF retrievals (OCO-2, TROPOMI), demonstrating that satellite derived SIF measurements could potentially diagnosis within and across season phenology at unprecedented spatial scales.

Inverse modeling and remote sensing of atmospheric properties provide an effective means to understand carbon sources and sinks on the land surface. For example, Hu et al., (2019) used atmospheric CO_2 observations (flask air measurements and continuous *in situ* measurements) and a high-resolution regional inverse modeling framework to explore the impact of El Niño–Southern Oscillation on carbon uptake in North America. Their results suggest that increased water availability and favorable temperature conditions (warmer spring and cooler summer) caused enhanced carbon uptake of 0.61 (0.45 to 0.79) PgC year^{-1} over North America near and during El Niño. This work demonstrates the need the include currently underrepresented regional carbon-climate relationships in terrestrial models. In another study, Maasakkers et al. (2019) leveraged GOSAT satellite measurements between 2010-2015 in a global inverse analysis to improve estimates of methane emissions and trends, as well as the global concentration of tropospheric OH (the hydroxyl radical, methane's main sink) and its trend over this time period. The attributed the observed growth in atmospheric methane between 2010–2015 to an increase in emissions from India, China, and areas with large tropical wetlands. The contribution from OH trends was small in comparison.

3. High Latitude Ecosystem Processes and Vulnerabilities

High latitude regions have some of the most rapidly changing and most vulnerable ecosystems on Earth. A significant amount of research has focused on detailing shifts in Arctic and boreal systems that are characterized by increasing temperatures, changes in vegetation structure, function, and composition, the persistent decline in ice thickness and summer extent of sea-ice cover, as well as atmospheric shifts.

The Arctic and Southern Oceans

The Arctic Ocean is becoming more and more ice-free during spring and summer, which, leads to decreased CO_2 uptake by the Arctic Ocean. According to findings by Lewis et al. (2019), sea ice loss is shifting the limiting resource of phytoplankton growth from light to nutrients (as phytoplankton quickly use up all the nutrients). This has had physiological consequences on phytoplankton, which were acclimated to grow under the high nutrient/low light levels found under the ice, maximizing photosynthetic rates and efficiency, and creating massive blooms beneath the sea ice. With less time to grow under sea ice, growth and photosynthetic rates are reduced due to severe nutrient limitation. In another study, Manizza et al. (2019) used a coupled ocean-biogeochemistry model to demonstrate that that the annual CO_2 sink of the Arctic Ocean decreased at a rate of 3.6 TgC a^{-1} between 2006–2013, due to a variety of processes that included changes in wind speed, primary production, and sea-ice area.

The Southern Ocean is getting 'greener'. Del Castillo et al. (2019) reported that, over the past 21 years, the amount of phytoplankton has been increasing, with more changes observed during the austral summer, which suggests that the growing season is getting longer for this region. The reason for this lengthening could be due to a variety of climate forcings and/or nutrient availability warranting more research considering the importance of the Southern Ocean in the biology and chemistry of the global ocean, and in regulating Earth's climate.

Arctic-Boreal Vulnerability Experiment (ABoVE)

New analyses from ABoVE have allowed better understanding of how key ecological properties are changing across space and time, and how these changes will impact the Earth system. Feedbacks from changing Arctic and boreal ecosystems accelerate climate change through carbon releases from thawing permafrost and higher solar absorption from reductions in Earth surface albedo, following loss of sea ice and land snow. Permafrost soils represent the largest terrestrial organic carbon pool (1330–1580 Gt) on Earth. While frozen, this soil carbon reservoir is stable. However, permafrost thaw generates carbon dioxide (CO_2) and methane (CH_4) constituting a positive feedback likely to amplify climate warming.

Walter-Anthony et al. (2018) demonstrated that carbon emissions from rapid thawing of permafrost beneath thermokarst lakes - shallow lakes that form when permafrost abruptly thaws and the land surface collapses - mobilizes ancient carbon and ultimately more than doubles previous estimates of the projected warming resulting from carbon release from the gradual thaw of permafrost. The loss of ancient carbon from abrupt thaw is irreversible on time scales relevant to policy; because even if the climate cools, deep thaw will persist and expand under thermokarst lakes. Once abrupt thaw becomes widespread, high CH_4 emissions will persist even if anthropogenic emissions are reduced, making it challenging to keep temperature increases below a 2° C target. These findings demonstrate the need to incorporate abrupt permafrost thaw in Earth system models to gain a more comprehensive understanding of the rate of projected climate warming throughout the 21st century.

High Latitudes and Economics
Carbon-climate feedbacks can also have a significant impact on the global economy. For example, Yumashev et al. (2019) used an integrated assessment economic model in combination with remote sensing data to estimate that feedbacks from permafrost thaw and non-linear reductions in surface albedo from disappearing snow and sea ice could increase the already substantial total cost of climate change by as much as an additional $66.9 trillion between 2017-2300. The total costs were based on economic impacts (e.g., damages from sea level rise, fire, war, etc.), mitigation costs, adaptation costs, and non-economic impacts such as public health. The scenarios used in this analysis were extended out to 2300 to capture the effects of multiple slow physical processes including the permafrost carbon feedback and the loss of the winter sea ice under high emissions pathways. Earlier work showed that a substantial fraction of the total discounted economic effects occur after 2100, so an analysis that ended in 2100 would be incomplete. While very long horizons like this may appear irrelevant from the point of view of the actual socio-economic processes, well-established technological, demographic and resource constraints imply that the range of scenarios is still plausible beyond the 21st century.

Boreal Ecosystems: Fire and Productivity
Boreal forest fires emit large amounts of carbon into the atmosphere primarily through the combustion of soil organic matter. During each fire, a portion of this soil beneath the burned layer can escape combustion, leading to a net accumulation of carbon in forests over multiple fire events. Walker et al., (2019) used radio carbon data ($\Delta^{14}C$ (the per-thousand difference between the $^{14}C/^{12}C$ ratio of the sample and an international standard) on 90 soil-depth increments as an index of soil age) from 211 field plots spanning seven spatially independent burn scars ion the Northwest Territories, CA during the first ABoVE field campaign. Fire history was developed with Landsat data for extent and burn severity. Results showed that climate warming and drying has led to more severe and frequent forest fires, which threaten to shift the carbon balance of the boreal ecosystem from net accumulation to net loss, resulting in a positive climate feedback.

Climate change has altered the vegetation composition and productivity of Arctic and boreal ecosystems in recent decades, with some ecosystems becoming more productive (greening) and others becoming less productive (browning). Field and UAV hyperspectral data were used in experimental ecosystem manipulation studies in boreal peatlands and demonstrated that vegetation leaf area and NDVI, a remote sensing measure of vegetation productivity, decreased (i.e., browning) with long-term reductions in soil moisture. However, warmer temperatures lead to an increase in the relative abundance of shrubs, which was also associated with increasing vegetation productivity and NDVI (McPartland et al., 2019). At larger spatial scales, there is some disagreement in Arctic greening/browning patterns as measured by satellites as well as with modeled estimates. These differences can largely be attributed to legacy effects from both natural and human induced disturbances. For instance, Tømmervik et al., (2019) examined changes in Eurasian forest area that quadrupled in recent decades, largely because of decreased human activities. Linear modelling suggested that the most important predictors for the variation in Eurasian forest biomass and area were logging, grazing and farming activity, and not climate change.

Rocha et al., (2018) used a modeling approach with the coupled carbon and nitrogen model (CCaN) to calculate a mass balance carbon and nitrogen model driven by MODIS surface temperature and climate (2000-2015). Results suggested that at longer temporal and larger spatial scales, MODIS greening trends were consistent with ecological and biogeochemical data from Arctic tundra. However, at smaller spatial scales, observations and CCaN greening trends differed in the location, extent, and magnitude of greening. CCaN was unable to capture the high rates of greening observed with MODIS observations in northern wetlands, as well as the patchy browning in the southern portion of the North Slope. This disagreement between model based and remote sensing derived greening and browning trends at smaller extents was attributed to several factors including soil impacts on vegetation, varying NDVI response between plant functional types, as well as disturbance induced land cover legacies.

4. Global vegetation dynamics and trends in Biodiversity

Research focused on leveraging remote sensing data to characterize and understand dynamics and trends of vegetation at global scales. Satellite data show increasing leaf area of vegetation suggesting an increasing productivity trend for global terrestrial vegetation. This increase is likely due to both direct factors (human land-use management) and indirect factors (such as climate change, CO_2 fertilization, nitrogen deposition and recovery from natural disturbances). Indeed, recent satellite data (2000–2017) reveal a strikingly prominent greening pattern in China and India which can be attributed to increasing cropland area in Indian and increased tree planting in China (Chen et al., 2019). In another study, Huang et al. (2018) examined three decades of remote sensing data to show that peak vegetation growth increased at global scales due to several factors including expanding croplands, rising atmospheric CO_2 concentrations, and regionally-dependent intensification of nitrogen deposition. This highlights the important roles of agricultural intensification and atmospheric changes in reshaping global vegetation growth dynamics.

Global temperature increases will also likely impact how well vegetation can grow and remove carbon from the atmosphere. Huang et a. (2019) used remote sensing data and flux data to demonstrate that the optimum air temperature for ecosystem productivity varies across the globe and that it is higher in warmer regions as compared to colder regions. In tropical forests in particular, the optimum air temperature for ecosystem productivity is already close to growing-season air temperature. However, future warming in these regions will likely exceed optimal air temperature, suggesting a more limited safe operating space for these ecosystems under future warming.

Most Earth system models agree that land vegetation will continue to store carbon due to the physiological effects of rising CO_2 concentration and climatic changes that favor plant growth in temperature-limited regions. However, there is some model disagreement on the amount of carbon uptake. Winkler et al. (2019) used an updated Leaf Area Index product from Global Inventory Modeling and Mapping Studies group (GIMMS) and Advanced Very High Resolution Radiometer (AVHRR) normalized difference vegetation index (NDVI) data (NDVI3g) and MODIS data to evaluate 36 years of plant productivity (Gross Primary Productivity – GPP). They also used CMIP5 carbon cycle model results and an atmospheric transport model to obtain prior information on anthropogenic carbon emissions as well as carbon exchange between atmosphere and land and ocean in the northern high latitudes to demonstrate that many models largely underestimate photosynthetic carbon fixation and therefore may overestimate future atmospheric CO_2 concentrations.

Methods for estimating photosynthesis from space commonly combine information on vegetation greenness, incoming radiation, temperature and atmospheric demand for water, but do not account for the direct effects of soil moisture, which limits photosynthesis when it is low (e.g., drought conditions). Stocker et al., (2019) compared several remote sensing GPP models (MODIS, MOD17A2H, VPM, BESS, and the P-model) with a globally distributed measurement network to assess the effect of soil moisture on photosynthesis. They identified a bias in satellite-based estimates of photosynthesis resulting from unaccounted soil moisture effects on vegetation productivity, suggesting that soil moisture effects reduce global annual photosynthesis by ~15%. These results demonstrate the importance of soil moisture effects for monitoring carbon-cycle variability and drought impacts on vegetation productivity from space.

5. Impact of Changing Climate on Biodiversity

Anthropogenic climate change, paired with increased human land use, poses serious threats to biodiversity globally. NASA satellite remote sensing is an important tool for monitoring biodiversity change and (in tandem with ecological models) predicting its future condition. Remote sensing allows for large-scale research with continuously updated information. In addition, there is no better means to track human expansion and associated changes across the entire globe than satellite remote sensing. Recent studies make use of MODIS, IKONOS, Landsat, and other remote sensing instruments and platforms to inform studies of tree coverage, plant productivity, and nutrient influxes.

Tree cover information (from MODIS and Landsat) and topography (from SRTM) were used to model the distribution and vulnerability of >19,000 species of amphibians, mammals, and birds across the globe. These relationships enabled prediction of future extinction risk using a range of land use change scenarios derived from the Shared Socioeconomic Pathways and Representative Concentration Pathways (2.6, 4.5, 7.0 and 8.5 W/m2) scenarios to the year 2070 (Powers and Jetz 2019). Substantial declines in suitable habitat were identified for species worldwide, with approximately 1,700 species expected to become imperiled due to land-use change alone.

Mathys et al. (2018) combined a simple physiological process-based model (3-PG) with a regeneration dataset using SRTM data (as a base for DEM) to compare the distribution of mature trees to saplings of four conifer species and predict range shifts due to changing climate conditions in British Columbia. Currently, saplings are vulnerable to dry conditions, which limit their establishment at southern latitudes and suggest a northern distribution shift into the future. Accounting for cohort differences such as seedling surveys in concert with tree surveys provide valuable ecological insights when predicting species responses to climate shifts. The negative impacts of drought frequency on plant productivity carries up through the food chain and lowers population abundance of mule deer and subsequently, mountain lion populations in the Great Basin, the Colorado Plateau, and the Mojave Desert of western North America (Stoner, et al., 2018). Using historical fire data from 1900-2015 to assess elk forage, Proffitt et al., (2019) found that more than fifteen years of increased drought and temperature rise have contributed to forest fires in the American West. Variability in the seasonality of fires, along with weather patterns provided important insight into forage quality and extent of habitat for elk populations in the Rocky Mountains of western Montana from six to fifteen years after fires.

Coastal and oceanic ecosystems are expected to change with climate. Furthering research in this area is critical to ensure that there is a better understanding of these changes, and potential impacts on resources on which humans depend on. For example, global increases in temperature are leading to poleward shifts of many species, and are pushing the boundaries of major biomes. Cavanaugh, et al., 2018 utilized MODIS, Landsat, and IKONOS imagery to examine relationships between mangrove abundance and climatic factors, specifically focusing on the range limits of mangroves in different regions of North and South America. They found that mangrove range limits in western North America and South America were not as sensitive to short-term climatic fluctuations as in eastern North America. In eastern North America, warming temperatures, along with a decreasing frequency of extreme cold periods, are increasing mangrove greening and range expansion poleward.

Previous research has indicated that the magnitude and timing of phytoplankton blooms may change due to increasing ocean temperatures and alterations to other ocean properties, which could have a direct effect on ecosystem services. However, recent studies suggest that relationships between ocean ecology and changing ocean conditions are more complex than previously thought. Record et al. (2019) examined phenological dynamics of phytoplankton blooms in the Gulf of Maine from 1960-2015 and found that both spring and autumn blooms shifted later in the year at rates ranging from ~1-9 days per decade since 1960, and trends only emerged at time scales >40 years. It was anticipated that spring blooms would occur earlier with warmer temperatures; and delays were attributed to changes in nutrient availability. They also reported implications of this shift on the sustainability of zooplankton populations, which in turn are fundamental for regional fisheries. At a broader scale, the question of how ocean ecology is changing in response to global climate change was investigated by Sharma et al. (2019), who utilized SeaWIFS data from 1990-2010 and analyzed changes in chlorophyll concentrations and phytoplankton. They found that, globally, biomass and the percent of large and small phytoplankton types is increasing in some regions, in response to increasing winds and mixing of the water column, while in other areas physiological changes may be responsible for some of the previously reported decreasing trends.

6. Carbon Export in Aquatic Ecosystems

Quantifying carbon fluxes in aquatic ecosystems and across its boundaries with the atmosphere and the land is critical for assessing the current state of the carbon cycle, and for projecting future trends in ocean carbon uptake, carbon export, and ocean acidification. In the coastal ocean, this is particularly important as this is an area of high carbon burial, and changes in carbon fluxes can impact the quantity of carbon sequestered to sediments. Increased coastal ocean acidification also has consequences for ecosystem services, such as shellfish farms, on which humans depend on. The second State of the Carbon Cycle Report (USGCRP, 2018) provides a current state-of-the-science assessment of the carbon cycle in North America (i.e., the United States, Canada, and Mexico), and its connection to climate and society. Several sections of the report specifically addressed coastal and open ocean regions, summarized recent progress in characterizing these carbon fluxes, and significantly advanced the current understanding of the North American carbon cycle and where gaps in this knowledge exist. One critical observation of this report was the need to maintain and expand existing ocean observing programs, as well as continuing coordinated work with stakeholders to ensure a healthier ocean, resilient communities, and stronger economies. Indeed, Turk et al. (2019) determined that for a **coastal** ocean acidification signal to emerge in North American ocean margins, it takes 23(±13) years, with considerable spatial variability, highlighting the need for sustained monitoring. Salisbury and Jönsson (2018) found that interannual and decadal variability in temperature and salinity in the Gulf of Maine can mitigate the expression of ocean acidification for pH, and that anomalies in temperature and salinity can impact the ocean's carbonate and ecosystem processes of calcifying organisms to a greater extent than just considering ocean acidification from increasing atmospheric carbon dioxide.

Lakes and rivers also can be significant pathways for the transport of mobilized terrestrial carbon to the ocean. In boreal watersheds, geophysical observations and cryohydrogeologic modeling provided insights into lateral perennial thaw zones in permafrost. Thaw zones altered subsurface flow and ultimately enhanced the terrestrial-to-aquatic transfer of carbon, nitrogen, and mercury previously sequestered in the frozen permafrost soil (Walvoord et al., 2019). Climate driven increases in permafrost thaw are expected to enhance the export of terrestrial organic carbon into many aquatic networks, yet the role that circumpolar lakes play in mineralizing this carbon remains unclear. A recent study by Bogard et al. (2019) evaluated ecosystem-scale organic carbon cycling for lakes of interior Alaska, an arid, low-relief lake landscape that is broadly representative of over a quarter of the total northern circumpolar lake area. They found that these lakes received very little organic carbon from ancient, thawing permafrost soils, and had small net contribution to the watershed carbon balance. Instead, most lakes recycled large quantities of internally derived carbon fixed from atmospheric CO_2, underscoring their importance as critical sites for material and energy provision to regional food webs. Changing lake area extant in arctic and boreal regions will continue to influence and regulate freshwater methane and CO_2 emissions. Observing these fine-scale changes in lake area has traditionally been difficult due to the coarse spatial and temporal resolution of available satellite imagery. However, a recent study by Cooley et al. (2019) demonstrated that high spatial resolution imagery (~3-5 m) from CubeSat imagery was effective for tracking fine scale lake area for ~85,000 lakes across Northern Canada and Alaska. They observed a general seasonal decline in lake area, but identified localized exceptions caused by wetland flooding and the growth and decline of vegetation on the lake surface. The greatest absolute lake area changes occurred in upland, lake-dense areas previously thought to be very stable. In these regions, small (<10 m) changes along lake margins cumulatively added up to large changes in total lake area that are largely undetectable from coarser-resolution satellites. This previously unquantified lake area variability suggests that models may underestimate greenhouse gas emissions from these regions.

In the open ocean, one pathway of carbon cycling and export that remains largely unquantified is the active transport of carbon from the surface ocean to the deep by zooplankton diurnal (diel) vertical migration. Archibald et al. (2019) developed a simple model driven by satellite measurements of net primary production, algal biomass, and phytoplankton size structure to quantify this carbon export. Their results show that the diurnal cycle of zooplankton vertical migration is an important contributor to carbon export from the surface, and also contributes to respiration (production of dissolved inorganic carbon) at depth. Understanding how different aquatic carbon cycling and export pathways may change in response to variable climate or biogeochemical conditions is critical to gaining a complete and predictive understanding of the global carbon cycle.

7. Coastal Ecosystem Health

Water quality research and monitoring in estuarine and coastal systems is important as these regions support a large fraction of the world's population. Water quality degradation as a result of human activity includes decreases in dissolved oxygen concentrations and increase nutrient loads. This has impacts on fish habitats, carbon fluxes, and ecosystems in general, many of which humans depend on for recreation and other economic activities. Systematic observations of water quality are crucial for assessing the state of estuarine and coastal aquatic habitats, but *in situ* measurements are often expensive and time consuming. New developments in satellite remote sensing platforms and algorithms, for example utilizing higher resolution measurements such as those from Landsat 8 (Luis et al. 2019) with *in situ* secchi disk measurements, as well as testing new unmanned aerial assets (Becker et al., 2019), provide powerful new tools to study and understand spatial and temporal aspects of water quality. In the Great Lakes, water quality issues (including harmful algal blooms) are particularly important as they continue to impact recreational and resource use of waterways in the region. Research supported by the NASA Glenn Research Center has advanced the understanding of algal blooms in the Great Lakes, and their consequences and impacts on human health. For example, it was determined through airborne hyperspectral imagery collected over Lake Erie, that in order to successfully differentiate algal bloom types based on their spectral reflectance, a spatial resolution of no more than 50 m is needed; this resolution provides the best sensitivity to high concentration areas that are of significant importance for human health and subject to potential ecological damage (Lekki et al., 2019). The Chesapeake Bay is an estuary which sustains a growing number of people, and one that has severe water quality issues. Irby and Friedrichs (2019) focused on nutrients in the bay, specifically evaluating two different models and the projected changes in water quality resulting from the implementation of regulatory standards which aim at reducing nutrient input. They developed a similarity Index that compared model results across habitat, time, and methodology, identifying locations and causes of greatest uncertainty in modeled projections of water quality. Estuary-ocean exchange of nutrients, oxygen, and carbon is also important for biogeochemical processing within an estuary. Signorini et al. (2019) used a neural network model, trained with *in situ* data and combined with satellite data, to characterize Chesapeake Bay estuarine export of dissolved organic carbon (DOC). DOC is a food supplement, supports growth of microorganisms and plays an important role in the global carbon cycle through the microbial loop, a marine pathway which incorporates DOC into the food chain. Using this novel methodology, an improved quantification of DOC export, riverine inputs, time scales of variability, and geomorphology to the East Coast coastal and estuarine carbon budgets. Results improved both quantification and understanding of biogechemical processes contributing to estuary-ocean exchange of carbon.

8. Field Campaigns

NASA supports several Earth Venture Suborbital (EVS) 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 has provided 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 that included Hawaii, the Great Barrier Reef, and other islands in the South Pacific. The CORAL project is about to complete its synthesis phase; over the past year, the team has finalized the processing of the airborne PRISM data and completed their field data analysis. The team is currently working on their publications, and preparing for the KDP-F (Evaluate the readiness of the project to conduct closeout activities including final delivery of all remaining project deliverables and safe decommissioning of space flight systems and other project assets), which is anticipated to take place in September, 2019.

The North Atlantic Aerosols and Marine Ecosystems Study (NAAMES; http://naames.larc.nasa.gov) is an interdisciplinary investigation to improve understanding of Earth's ocean ecosystem-aerosol-cloud system. It combines atmospheric and oceanographic airborne and ship observations with continuous satellite sensor records to characterize plankton ecosystem properties and their dependence on environmental forcings, determine how different phases in the annual cycle interact to recreate each year the conditions for the plankton bloom, and resolve how remote marine aerosols and boundary layer clouds are influenced by plankton ecosystems. Four NAAMES field campaigns were conducted in the western subarctic Atlantic between November 2015 and April 2018, with each campaign targeting specific seasonal events in the annual plankton cycle. This EVS project is nearly complete and the team held their final science team meeting in June 2019. To date, the project has published over 20 peer-review articles, with five in the journal *Nature* and many others under review. Behrenfeld et al. (2019) published a thorough overview of NAAMES science motives, experimental design, and measurements, as well as some of the main accomplishments achieved during the project's lifetime.

The EXport Processes in the Ocean from RemoTe Sensing (EXPORTS; https://oceanexports.org) project successfully completed their first major field campaign in the North Pacific in August-September 2018 which involved two research vessels as well as a wide array of autonomous platforms to complement the shipboard data. EXPORTS goal is to improve predictions of the export and fate of ocean NPP using satellite data and numerical models, thereby advancing the utility of NASA ocean color assets. The science team held their second Science Team meeting in May 2019, where initial results from the 2018 field campaign were showcased and discussed. The team is preparing for their second, and final, field campaign in the North Atlantic in April/May 2020, which is a contrasting endmember in terms of ecosystems and circulation dynamics to the North Pacific. The success of EXPORTS has drawn in other national and international partners, and EXPORTS is currently collaborating with WHOI's Ocean Twilight Zone (OTZ) Project. The OTZ will add a third ship to the North Atlantic and conduct side-by-side sampling with EXPORTS, focusing on higher trophic level processes and measuring other EXPORTS-complementary parameters. EXPORTS is also a central partner to the international BIARRITZ workshop (https://noc.ac.uk/project/biarritz), which focuses on the Twilight Zone and aims at bringing together projects worldwide that are focused on better characterizing carbon export to depth. The BIARRITZ workshop will take place July 22-26, 2019.

NASA's Arctic and Boreal Vulnerability Experiment (ABoVE) is a 10 year field campaign focused on understand how rapid change in the Arctic and boreal North America is impacting ecosystem structure and function and social systems the rely on services from these ecosystems. The region of interest for ABoVE is Alaska and northwestern Canada. ABoVE successfully completed a second airborne data collection campaign in 2018. The 2018 airborne campaign collected remote sensing datasets including hyperspectral data using Next Generation Airborne Visible Imaging Infrared Spectrometer (AVIRIS-NG), radar data (L-band SAR) using UAVSAR, Goddard's LiDAR, Hyperspectral & Thermal Imager (G-LiHT), and full waveform Light Detection and Ranging (LiDAR) laser light data. Targets of interest included field sites occupied by the ABoVE Science Team as well as the intensive sites operated by the Department of Energy's Next Generation Ecosystem Experiment-Arctic on the Seward Peninsula and in Barrow, the National Science Foundation's Long Term Ecological Research sites at Toolik Lake (Arctic/North Slope) and Bonanza Creek (Boreal/Interior Alaska), as well as numerous sites in Canada of interest to several Canadian research and governmental partners. In addition, to airborne data collection, the ABoVE supported a wide variety of field data collection activities involving approximately 14 different funded research teams accessing field sites across Alaska and Western Canada.

NASA launched the Global Ecosystem Dynamics Investigation (GEDI) instrument to the International Space Station in late 2018. GEDI was a mission selected in July 2014 through the Earth Venture Instrument 2 solicitation. The GEDI instrument is mounted on the International Space Station's Japanese Experiment Module – Exposed Facility and is a full-waveform lidar instrument that makes detailed measurements of the 3-dimensional structure of the Earth's forests and land surface to ultimately build a map of global forest biomass at a 1 km spatial resolution. GEDI finished its on-orbit checkout phase (the commissioning period) and started official operations to acquire science data on March 25th, 2019. GEDI is currently following Reference Ground Tracks to evenly sample the forest structure across the Earth, and is on-target to exceed the goal of collecting approximately 10 billion cloud-free observations of the Earth's surface during its nominal two-year mission life. Additionally, recent research has demonstrated that integrating GEDI data with globally available synthetic aperture radar data (e.g., DLR's TanDEM-X), improves the accuracy of biomass maps and increases spatial resolution from 1km to 25m (Qi et al., 2019).

9. Community Meetings

Several countries in South and Southeast Asia are undergoing rapid changes due to urbanization and industrial development. The population growth together with rapid economic development is causing immense pressure to convert land from forest to agriculture and from agricultural areas to residential and urban uses with significant impact on ecosystem services. Increased Land Cover/Land Use Change (LCLUC) in the region is disrupting and perturbing atmosphere, forest resources, biodiversity, regional climate, biogeochemical cycles, water resources, and other ecosystem services. July 22-24, 2019, NASA's LCLUC program, in concert with many international sponsors hosted a workshop on Land Use/Cover Changes, Environment and Emissions in South/Southeast Asia in Johor Bahru, Malasia.

The aim of this meeting was to review the availability, potential, and limitations of different data sources and methodologies for the monitoring and the study of LCLUC, and quantification and its impact on the environment. The meeting presentations focused on synergies among various approaches bridging scientific research and applications, and provide recommendations on how to improve the use of Earth observations, ground data and modeling techniques to understand and quantify land use changes on Earth system science.

Ocean Optics XXIV was held in Croatia, October 7-12, 2018. This bi-annual conference attracts a diverse international audience of active practitioners in ocean optics, including oceanographers, marine ecologists, limnologists, optical engineers, marine resource managers, and policy professionals. Presentations in the XXIV conference focused on research and applications of optics in aquatic environments, including biogeochemistry, environmental management and applications, instruments and novel in situ and remote sensing techniques, and observational systems. The conference offered also workshops and short courses, such as the SeaDAS Training led and sponsored by NASA.

The fourth International Ocean Colour Science (IOCS) meeting took place from 9 to 12 April 2019 in Busan, South Korea. The meeting was convened by the International Ocean Colour Coordinating Group (IOCCG). This bi-annual meeting serves as a venue to bring together the international scientific and application communities with space agencies, and discuss priorities, ideas and perspectives. The NASA Ocean Color Research Team (OCRT) meeting took place in conjunction with the IOCS meeting on 8 April, 2019. The overarching theme for IOCS-2019 was "Fostering International Collaboration in Multi-Scale Ocean Colour Science and Applications", with the overall goal of nurturing a strong global user community for ocean color science and applications. The meeting also hosted the SeaDAS Training, led and sponsored by NASA.

The NASA Biodiversity and Ecological Forecasting Team Meeting took place May 21-23, 2019, with over 155 people in attendance. In addition to dozens of project talks and posters, the second afternoon of the meeting featured trainings and tutorials focused on new tools developed through the programs as well as a session on story-telling. These sessions were a hit.

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FY 2019 Annual Performance Indicator	FY 16	FY17	FY18	FY19
ES-19-6: 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

<u>Annual Performance Indicator ES-19-7:</u> Demonstrate planned progress in enabling better assessment and management of water quality and quantity to accurately predict how the global water cycle evolves in response to climate change.

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.

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 and NISAR), 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 FY2019 and represent research that has been funded over the past several ROSES cycles.

<u>Water Budget and Water Cycle Dynamics</u>

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 begins with three cross-cutting publication that are followed by subsections that highlight water budget and cycle research related to snow, surface water, soil moisture, and groundwater.

Persistent changes to the regional snowpack in a changing climate can have disruptive societal and economic impacts (water supply, agriculture, and regional flooding for example). In a review of snow pack trends, Bormann *et al.* (2018: *Nature Climate Change*) found that there is extensive surface and satellite-based evidence of significant declines in the spring snow cover in Northern Hemisphere starting in the mid 1980's. They attribute the decline in snowpack as a response to recent warming. They also found that our ability to monitor snow cover and trends in mountain regions is severely hampered by limitations in current satellite systems, consequently the trends in the mountains are much less clear.

For years, scientists and engineers have been using aerial photography to study the shapes of rivers, how they change over time, and how they relate to other river characteristics, such as river width, the slope of the water surface, and flow. Frasson *et al.* (2019: Geophys. Res. Lett.) integrated Landsat derive river centerlines with the Shuttle Radar Topography Mission digital elevation model to created spatially continuous maps of mean annual flow river width, slope, meander wavelength, sinuosity, and catchment area for all rivers wider than 90 m located between 60°N and 56°S. They analyzed the distributions of these properties, identified their typical ranges, and explored relationships between river planform and slope and found that river width to be directly associated with the magnitude of meander wavelength and catchment area. They also found that that narrower rivers show a larger range of slope and sinuosity values than wider rivers. Finally, by comparing simulated discharge from a water balance model with measured widths, they showed that power laws between mean annual discharge and width can predict width typically to −35% to +81%, even when a single relationship is applied across all rivers with discharge ranging from 100 to 50,000 m^3/s.

Time-resolved satellite gravimetry has revolutionized understanding of mass transport in the Earth system. Since 2002, the Gravity Recovery and Climate Experiment (GRACE) has enabled monitoring of the terrestrial water cycle, ice sheet and glacier mass balance, sea level change and ocean bottom pressure variations, as well as understanding responses to changes in the global climate system. Tapley *et al.* (2019: *Nature Climate Change*) outlined many of the overarching discoveries from GRACE spanning multiple science disciplines (cryosphere, hydrology, sea level change/ocean dynamics, and climate service applications), with a preview of the measurements from the GRACE-FO Mission: the WEC GPRA synthesis will focus on contributions to the Focus Area. Among the most impactful contributions of the GRACE mission has been in the unveiling of Earth's changing freshwater landscape, which has profound implications for water, food and human security. Global estimates of GRACE trends suggest increasing water storage in high and low latitudes (wetting), with decreased storage in mid-latitudes (drying). Even though the GRACE record is relatively short, this observation of large-scale changes in the global hydrological cycle has been an important early confirmation of the changes predicted by climate models through the twenty-first century. Of the world's 37 largest aquifer systems, 13 were found to be suffering critical depletion during the GRACE observational period, with many linked to anthropogenic activities. Additionally, they found that the integration of GRACE TWS data and other observations within a land-data assimilation system has been shown to produce significant improvement in the accuracy of drought tools, such as the US Drought Monitor. Likewise, they also found that GRACE derived products improved flood forecasts.

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 the North America snow cover trends (described above), snow melt timing, and snow cover fraction assessment. The two highlighted publications below include results from one of the SnowEX projects and a promising new approach to resolve SWE with passive microwave.

As new remote sensing techniques are developed, it is critical to recognize, characterize and understand any potential systematic biases in the validation of the new approaches with known capabilities. One of the objectives of NASA's 2017 SnowEx field campaign at Grand Mesa, CO, was to enable cross validation of techniques. Currier *et al.* (2019, Water Resources Research) collected Airborne Laser Scans (ALS), Terrestrial Laser Scans (TLS), and snow-probe transects and compared the snow depth measurement techniques. They found that gridded (1 m) ALS and TLS observations had a median snow depth difference of 5 cm with an RMS difference of 16 cm. The greatest disagreements were where snow-off TLS scans had shrubs and high incidence angles, leading to deeper snow depths (>10 cm) from ALS than TLS. The low vegetation and oblique angles caused occlusion in the TLS data and thus produced higher snow-off bare Earth models relative to the ALS. They conclude that ALS captured snow depth magnitude with better than or equal agreement to what has been reported in previous studies and showed the ability to capture high-resolution spatial variability.

Seasonal snow cover plays an important role in hydrologic and climate systems, as well as in natural hazards such as floods and avalanches. Mountain snowpack acts as a natural reservoir during the winter accumulation season; spring snowmelt supplies critical water resources for agricultural, ecological and domestic uses in the western United States and accounts for >70% of streamflow volume. Kim *et al.* (2019: *Remote Sensing of Environment*) developed a physically-based snow depth retrieval algorithm adapted for deep mountainous snowpack that combined airborne multifrequency (10.7, 18.7, 37.0 and 89.0 GHz) passive microwave (PM) radiance observations with an ensemble framework for snowpack model. They found that PM measurements can be used to estimate snow depth even when snow is deep because microwave brightness temperatures continue to carry information about snow depth (and, thus, about snow water equivalent) even for deep snow. Their approach was able to achieve accurate snow depth estimation, with R2 = 0.85, and RMSE = 13.3 cm, despite the observed snow depths being in the range of 100–300 cm in open terrain and the approach perform better in light forest cover (<30%) if they considered the effect of forests on microwave radiative transfer altogether. Overall, this study showed that it is possible to estimate SWE in global mountains using passive microwave measurements.

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 time-series data from GRACE-FO missions mature, technology and algorithm development are beginning to support new scientific advancements with increasing contributions in future GPRA cycles. There were 18 publications that past GPRA cycle that spanned a variety of surface water related science and technique development ranging from more comprehensive regional studies (i.e. Yukon, Saint-Venadat, and Mekong Rivers) to exploring new capabilities with ICESat-2. The three featured publications seek to better characterize surface water dynamics through different approaches: satellite radar/SAR, GNSS Reflectometry, and AirSWOT measurements.

Measuring the water flux in large river basins, such as the Amazon River, is challenging because the water flow is not constrained to a single river channel where stream gages measure water flow, rather there are complex hydrodynamic process that govern water flow through wetlands and floodplains that require a broader synoptic measurement approach. Cao *et al.* (2018: *Remote Sensing*) estimate water level changes ($\partial h/\partial t$) over wetlands and floodplains from ALOS PALSAR SAR (JAXA) interferograms in the Amazon Basin and compared the results with ARgos and ALtiKa (SARAL: joint mission by ISRO and CNES) satellite altimetry's ($\partial h/\partial t$) reference data for the same time period. They found that the local $\partial h/\partial t$ patterns of Amazon floodplains are spatially complex with highly interconnected floodplain channels and that the broad flow patterns can be characterized by the overall river water flow directions. They also found that the spatial resolution and coherence of the ALOS-2 fine-beam InSAR interferograms (narrower swath width, higher resolution imagery) are generally better than wider ScanSAR interferograms, which means the fine-beam interferograms can capture more accurate spatial variation of the $\partial h/\partial t$ patterns and obtain better $\partial h/\partial t$ estimate accuracy. However, the large-scale $\partial h/\partial t$ patterns cannot be directly obtained from mosaicking fine-beam images since $\partial h/\partial t$ changes rapidly in floodplains with respect to the collection frequency of ALOS. Therefore, even though the accuracy of the ScanSAR estimates were not as good as the fine-beam data, they found that it was still necessary to process the wide-swath ScanSAR datasets to obtain large-scale ∂h/∂t maps. The approach would be transferable to other tropical basins.

Mapping the spatial and temporal variability of inundation in tropical wetlands remains a significant challenge because of low sensor spatial resolution or temporal fidelity and because of limitations imposed by cloud cover. Jensen *et al*. (2018: *Remote Sensing*) compared the capability of Global Navigation Satellite Systems Reflectometry (GNSS-R) with respect to imaging radar (SAR) to characterize surface inundation dynamics in a tropical wetlands complex to assess capabilities of each and potential for synergistic use of these technologies for mapping inundation dynamics under dense tropical forest canopies. They examined JAXA PALSAR-2 L-band radar, CYGNSS GNSS-R, and ground measurements of vegetation structure and surface inundation and found that the capability of CYGNSS for mapping wetland extent and inundation dynamics in complex tropical landscapes, alone or in combination with other remote-sensing techniques such as those based on imaging radar, contributed to enhanced mapping of these regions. CYGNSS data were useful in mapping relatively high resolution (~1 km) changes in inundation extent with high temporal fidelity (~7 days), which will allow for better mapping of inundation dynamics in tropical wetlands, providing the potential for stand-alone mapping of inundation processes or extending the utility of existing techniques, such as SAR.

There have been a number of different methods developed to estimate river discharge in anticipation of 2022 launch of SWOT, but many have yet to be tested on real-world data at the spatial scales and accuracies expected of SWOT. Tuozzolo *et al*. (2019: *Geophysical Research Letters*) tested three discharge algorithms on data collected by AirSWOT, the airborne SWOT testbed, that collected imagery over the Willamette River in Oregon, USA. They found that river discharge can be estimated by these algorithms with encouraging accuracy (10–31%) using only airborne measurements and a model-derived estimate of the mean annual discharge. They stress the need for further testing of these algorithms to determine their sensitivities to the initial estimate of flow and the hydraulic character of the river reach but suggest that these results are encouraging for future global-scale deployment of SWOT discharge algorithms.

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. 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 highlights a small subset of the overall soil moisture research that was published during this GPRA cycle, fully building on SMAP and GRACE while exploring a variety of new and innovative approaches.

The SMAP active radar (HiRes: ~3 km resolution) and passive (LoRes: ~ 36 km) co-collected imagery for nearly 2.5 months. Das *et al*., (2018: *Remote Sensing of Environment*) applied the radar-radiometer observations fusion algorithm to obtain brightness temperature (Tb) on a 9 km grid and 3 km grid and retrieve soil moisture at 9 km and 3 km from downscales Tb from SMAP's extensively validated SMAP retrieval algorithm. Their new soil product revealed high resolution spatial features that were not apparent in the original 36 km product. Subsequent validation using long-term *in situ* soil moisture data confirmed that the new product exhibits a retrieval accuracy better than 0.04 m^3/m^3 (mission requirement) at 9 km and 0.06 m^3/m^3 at 3 km over nominal land cover types. The validated high-resolution active-passive global soil moisture products are available at: http://nsidc.org/data/SPL2SMAP

There is currently no single approach that can estimate the water storage components across the soil column as a whole, from the surface soil moisture down to the shallow (unconfined) groundwater (typically at depths less than 4 m). Girotto *et al.* (2019: Remote Sensing of Environment) combined GRACE TWS (Terrestrial Water Storage), SMOS (ESA), SMAP, AMSR-E, and MODIS products in a multi-sensor and multi-scale data assimilation model to 1) quantify the improvements of hydrological estimates via single-sensor and multi-sensor assimilation of GRACE TWS and SMOS observations through validation with in-situ measurements; and 2) understanding the impact of each assimilation system on the soil moisture profile estimates through an analysis of the associated assimilation diagnostics. As expected, their study had a number of key findings (too numerous to describe here); overall, the assimilation models benefited from the multi-sensor integration, however, there were a few surprises finding such as the GRACE+SMOS DA data were anti-correlated.

It is generally accepted that year-to-year variability in moisture conditions and drought are linked with increased wildfire occurrence. However, quantifying the sensitivity of wildfire to surface moisture state at seasonal lead-times has been challenging due to the absence of a long soil moisture record with the appropriate coverage and spatial resolution for continental-scale analysis. Jensen *et al.* (2018: *Environmental Research Letters*) apply model simulations of surface soil moisture that numerically assimilate observations from GRACE with the Forest Service Fire-Occurrence Database over the contiguous US and quantify the relationships between pre-fire-season soil moisture and subsequent-year wildfire occurrence by land-cover type and produce annual probable wildfire occurrence and burned area maps at 0.25° resolution. They find that cross-validated results generally indicate a higher occurrence of smaller fires when months preceding fire season are wet, while larger fires are more frequent when soils are dry. This is consistent with the concept of increased fuel accumulation under wet conditions in the pre-season. These results demonstrate the fundamental strength of the relationship between soil moisture and fire activity at long lead-times and are indicative of that relationship's utility for the future development of national-scale predictive capability.

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.

Groundwater plays a major role in the water and ecological cycles in large tropical river basins with large influences on the rainforest ecosystems and climate variability. However, the changes in groundwater storage are not known because there is a lack of monitoring networks. Frappart *et al.* (2018: *Adv. Water Resources*) estimated the spatio-temporal variations of groundwater storage over between January 2003 to September 2010 in the Amazon Basin by decomposing the total terrestrial water storage measured by GRACE into the individual contributions of other hydrological reservoirs, using multi-satellite data for the surface waters and floodplains, and using model outputs for the soil moisture. They found that the seasonal variations of groundwater storage represent between 20 and 35% of the terrestrial water storage seasonal volume variations of the Amazon. Larger seasonal amplitudes of groundwater storage (>450 mm) were resolved in the in the central part of the Amazon Basin.

Highly managed aquifer systems present a challenge for Advanced Land Surface Models (LSM), which typically have simplified or incomplete representations of human water use. Nie *et al.* (2018: *Water Resources Research*) examine recent groundwater declines in the US High Plains Aquifer (HPA), a region that is heavily utilized for irrigation and that is also affected by episodic drought to understand observed decline in groundwater and terrestrial water storage during a recent multiyear drought. They modify the Noah-MP LSM to include a groundwater irrigation scheme to account for seasonal and interannual variability in active irrigated area and found that by including the groundwater irrigation scheme improves model agreement with ALEXI ET data, mascon-based GRACE TWS data, and depth-to-groundwater measurements in the southern HPA, including Texas and Kansas. Their findings for the HPA in Nebraska were mixed, likely due to the model's weaknesses in representing subsurface hydrology in this region. This study highlights the value of GRACE data sets for model evaluation and development and the potential to advance the dynamic representations of the interactions between human water use and the hydrological cycle.

High Mountain Asia

The Himalayan mountain glaciers encompasses the largest reservoirs of freshwater on Earth outside of the polar regions. The melting of snow and glaciers in High Mountain Asia (HMA) contributes up to 70% of the annual water supply of over 1.4 billion people in the region. In 2015, NASA formed the High Mountain Asia Science Team (HiMAT) as an interdisciplinary science team that focused on studying glaciers, snow, permafrost, and precipitation to improve our understanding of regional changes, water resources, and induced impacts, while furthering NASA's strategic goals in Earth system science and societal applications. The first set of WEC related studies from HiMAT that focused on evaluating the uncertainty of the terrestrial water budget and water storage trends in High Mountain Asia.

Yoon *et al.,* (2019*: Frontiers in Earth Science)* explored the uncertainties in terrestrial water budget estimation over High Mountain Asia (HMA) using a suite of uncoupled land surface model (LSM) simulations. They found that the uncertainty in the water balance components of precipitation, ET, runoff, and terrestrial water storage (TWS) was significantly impacted by the uncertainty in the driving meteorology, with precipitation being the most important boundary condition. Furthermore, a comparison of ET, snow cover fraction, and changes in TWS estimates against remote sensing-based references confirms the significant role of the input meteorology in influencing the water budget characterization over HMA and points to the need for improving meteorological inputs.

Loomis *et al.* (2019: *Frontiers in Earth Science)* sought to quantify and close the budget of secular changes in TWS over the span of the GRACE (2003–2016) utilizing new high-resolution mass trend product from GRACE L1B data, glacier mass balance derived from Digital Elevation Models (DEMs), groundwater variability determined from confined and unconfined well observations, and terrestrial water budget estimates from a suite of land surface model simulations with the NASA Land Information System (LIS). They found that the total mass trends for the geodetic glacier mass balance and groundwater observations were -19.0 Gt yr^{-1} and -13.6 Gt yr^{-1} over their respective sub-regions within HMA. Summing these values results in a combined mass trend of −32.6 Gt yr^{-1}. Furthermore, they found that the trend in unconfined groundwater alone was positive (+2.0 Gt yr^{-1}) and well outside the uncertainty range of the GRACE trend, but when combined with the confined trend results in a trend of −13.6 Gt yr^{-1}. Though agreement with GRACE in this region is not achieved, it is clear that the confined groundwater is a significant contributor to the GRACE-derived trend in HMA.

Global precipitation, evaporation, and land-atmosphere coupling

The WEC leverages the investments of other focus area programs to create, refine, and use long time scale assessments related to precipitation and air-sea 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 as well as assess potential geohazards associated with precipitation events.

Precipitation is a key variable in the overall water cycle and is an essential boundary condition for many numerical models: research on precipitation is reported in the Weather and Atmospheric Dynamics Focus Area and for the WEC. Water balances have larger uncertainties in mountain regions, where orographic processes produce high spatial variability in precipitation patterns and snow accumulation. Recent work suggests current water budgets underestimate mountain snow water storage, perhaps indicating biases in modeled precipitation. Wrzesien *el al.* (2019: *Water Resources Research*) assessed if global hydroclimate data sets underestimate precipitation for six North American watersheds that ranged from 3–70% mountains. They compared relatively high-resolution precipitation estimates from the Weather Research and Forecasting (WRF) regional climate model with four global products. They found that every climate model underestimated the total rainfall in mountainous terrain but performed significantly better in flat terrains. For example, the Modern-Era Retrospective Analysis for Research and Applications version 2 and the Global Land Data Assimilation System showed smaller underestimates relative to WRF (−17% and −21%, respectively), with nearly all mean bias from the mountains (underestimated by 27% and 39%) rather than the topographically simpler lowlands (underestimated by 5% and 2%). This study suggested that global products fail to capture orographic enhancement of precipitation, resulting in large underestimates of precipitation, snowfall, and snow water storage in mountains of selected North American watersheds, which highlights the need for more accurate precipitation estimates to accurately assess spatiotemporal variations in the water cycle.

Precipitation extent, rate, and duration are critical parameters in understand fluvial hazards such as floods, debris flows and shallow landslides. Kirschbaum *et al.* (2018: *Earth's Future*) developed a Landslide Hazard Assessment for Situational Awareness (LHASA) model that identified potential landslide activity in near real-time. Their approach integrated 7-day satellite-based precipitation estimates (GPM) conditions with a landslide susceptibility map derived from geophysical parameters (i.e. slope, geology, etc.) and forest loss and provided near real-time situational awareness of landslide hazards. It was noted that their approach could leveraged nearly two decades of satellite precipitation data to better understand long-term trends in potential landslide activity. Yatheendradas *et al.* (2019: *Computational Geosciences*) performed a higher resolution regional rainfall trigger landslide investigation in North Carolina using the Transient Rainfall Infiltration and Grid-based Regional Slope-stability analysis (TRIGRS) model that utilized the TRMM Multi-satellite Precipitation Analysis (V7), the North American Land Data Assimilation System Phase 2 (NLDAS-2) analysis, and the reference "truth" Stage IV precipitation. As expected, the study had a number of results that linked rainfall with known landslides. However, relevant to WEC objectives, they found at higher elevations that both TMPA and NLDAS-2 precipitation volumes were insufficient.

Land-Atmosphere Coupling

The land surface is coupled to the atmosphere through water and energy fluxes. As a consequence of this coupling, poor representation of land surface processes can contribute to prediction biases and errors in weather and climate models. In numerical atmospheric models, the degree to which the atmosphere responds to anomalies in land surface state (the "coupling strength") is a net result of complex interactions between numerous physical process parameterizations, such as those for evapotranspiration, boundary layer development, and moist convection. Soil moisture and vegetation state are important in characterizing the influence of the land surface on surface energy partitioning. We highlight two publications that seek to better understand land-atmosphere coupling.

Forecast errors with respect to wind, temperature, moisture, clouds, and precipitation largely correspond to the limited capability of current Earth system models to capture and simulate land–atmosphere (L–A) feedback. Wulfmeyer *et al.* (2018: *Bulletin of the*

American Meteorological Society) developed an innovative ground-based, scanning active remote sensing systems for 2D to 3D measurements of wind, temperature, and water vapor from the surface to the lower troposphere that can provide comprehensive datasets for characterizing L–A feedback independently of any model input. Their study described research activities for the improvement of the next generation of weather forecast, climate, and Earth system models. As the resolutions used in model systems approach the gray zone of turbulence, new and scalable combinations of the parameterization of surface fluxes and PBL (planetary boundary layer) turbulence in heterogeneous terrain need to be developed and tested. The deficiencies in current parameterizations have to be detected and suggestions for their improvement have to be made as these problems are leading to suboptimal representations of L–A feedback and, thus, to errors in the representation of the diurnal cycle of PBL dynamics and thermodynamics including the simulation of convection initiation. An experimental design taking advantage of the sensors' synergy and advanced capabilities was realized for the first time during the Land Atmosphere Feedback Experiment (LAFE), conducted at the Atmospheric Radiation Measurement Program Southern Great Plains site in August 2017.

Dirmeyer *et al.* (2018: *Journal of Hydrometeorology*) utilized the updated FLUXNET2015 synthesis dataset for a global assessment of surface energy and water balance simulations and basic metrics of land–atmosphere coupling. They found that many of the long-known problems and biases in global models of the land–atmosphere coupling portion of the climate system still exist. Nevertheless, there is a fair degree of compensation among errors, such that model representations of land–atmosphere coupling often appear fairly good. Some targets for modeling improvement are clear, however, problems may lie in our limited understanding of the numerous process entwined in coupled linkages. The representation of surface albedo LSM and the quantities of downward radiation at the surface (GCM) need improvement among the energy cycle terms, along with the partitioning of available energy between latent and sensible heat flux. Precipitation errors remained large, and inconsistencies in representing soil moisture among models and between models and nature remain stubborn issues.

Water – Ecosystem / Evapotranspiration / Drought

WEC seeks to better 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 four studies below are advancing our understanding about the water-ecosystem/agriculture interface during droughts and in semi-arid ecosystems.

Characterizing and understanding the water mass balance of a hydrologic basin is both extremely challenging and important, especially in managed basin in arid environments. Singh *et al.* (2018: *Remote Sensing*) is an in-depth analysis of the mass balance of the South Aral Sea and its basin, where they estimate lake volume, evaporation from the lake, and the Amu Darya streamflow into the lake using multiple instruments from ground and space. For example, in one of their variable analysis, they found terrestrial water storage (TWS) variations observed by the Gravity Recovery and Climate Experiment (GRACE) mission from the Aral Sea region can approximate water level of the East Aral Sea with good accuracy (1.8% normalized RMSE) against satellite altimetry observations. In this comprehensive analysis, they found that the spatiotemporal pattern in the Amu Darya basin shows that terrestrial water storage (TWS) in the central region (predominantly in the primary irrigation belt other than delta) has increased. This increase can be attributed to enhanced infiltration, as ET and vegetation index (i.e., normalized difference vegetation index (NDVI)) from the area has decreased. The additional infiltration might be an indication of worsening of the canal structures and leakage in the area. The study shows how altimetry, optical images, gravimetric and other ancillary observations can collectively help understand and characterize the water mass balance in arid basins.

Cooley *el al.* (2018: *Ecological Applications*) investigated the ecological responses to drought by developing a conceptual framework of vegetation response and investigating how multiple measures of drought could improve regional drought monitoring. They applied their approach to a case study of a recent drought in Guanacaste, Costa Rica. They assessed drought severity with the Standard Precipitation Index (SPI) based on a 64-yr precipitation record derived from a combination of Global Precipitation Climatology Center data and satellite observations from TRMM and GPM. They examined the spatial patterns of precipitation, vegetation greenness, evapotranspiration (ET), potential evapotranspiration (PET), and evaporative stress index (ESI) during the drought years of 2013, 2014, and 2015 relative to a baseline period (2002–2012). They found that that rainfall in Guanacaste reached an all-time low in 2015 over a 64-yr record (wet season SPI = −3.46), resulting in NDVI declines. However, ET and ESI did not show significant anomalies relative to a baseline, drought-free period. Forests in the region exhibited lower water stress compared to grasslands and had smaller declines, and even some increases, in NDVI and ET during the drought period. This work highlights the value of using multiple measures to assess ecosystem responses to drought.

Estimating terrestrial evapotranspiration (ET) on continental to global scales is central to understanding the partitioning of energy and water at the earth surface and for evaluating modeled feedbacks operating between the atmosphere and biosphere. ET is an important flux that links the water, carbon, and energy cycles. Holmes *et al.* (2018: *Hydrology and Earth System Sciences*) showed that a newly developed microwave-land surface temperature (MW-LST) product can be used to effectively substitute thermal infrared-(TIR) based LST in a two-source energy balance approach to estimate coarse-resolution ET (~ 25 km) from space. They found that that the long-term bulk ET estimates from both LST sources agree well, with a spatial correlation of 92 % for total ET in the Europe–Africa domain and agreement in seasonal (3-month) totals of 83–97 % depending on the time of year. Most importantly, the ALEXI-MW (MW-based ALEXI) also matches ALEXI-IR (IR-based ALEXI) very closely in terms of 3-month inter-annual anomalies, demonstrating its ability to capture the development and extent of drought conditions. The concluded that a constellation of MW satellites could effectively be used to provide LST for estimating ET through ALEXI, which is an important step towards all-sky satellite-based retrieval of ET using an energy balance framework.

Accurately estimating evapotranspiration (ET) over West Africa is particularly important for water resources management, weather monitoring and climate change impact assessment on agriculture and food security due to a strong land-atmosphere coupling. Jung *et al.* (2019: *Remote Sensing*) developed an ET ensemble composed of 36 land surface model (LSM) experiments and four diagnostic datasets (GLEAM, ALEXI, MOD16, and FLUXNET) to investigate uncertainties in ET estimate over five climate regions in West Africa. They found that the diagnostic ET datasets show lower uncertainty estimates and smaller seasonal variations than the LSM-based ET values, particularly in the humid climate regions. Overall, the impact of the choice of LSMs and meteorological forcing datasets on the modeled ET rates increases from north to south. The LSM formulations and parameters have the largest impact on ET in humid regions, contributing to 90% of the ET uncertainty estimates. Precipitation contributes to the ET uncertainty primarily in arid regions. The LSM-based ET estimates are sensitive to the uncertainty of net radiation in arid region and precipitation in humid region.

Data Modeling/Assimilation

The accurate quantification of terrestrial water and energy cycles is important for a wide range of applications including weather and climate modeling and initialization, agricultural and water management and estimation of hydrological hazards such as droughts and floods, among others. The need for robust estimates of land surface conditions to support terrestrial water and energy cycles applications has led to the development of land data assimilation systems (LDASs) for data modeling and assimilations. These systems combine high-quality observations from in situ networks with remote sensing measurements and products to generate an improved representation of land surface processes. The synthesis of several types of model and observation data across various spatial and temporal resolutions supports the development of flexible LDAS configurations for conducting both research and application-oriented studies. Three studies are summarized below.

Kumar *et al.* (2019: *Journal of Hydrometeorology*) developed a multisensor, multivariate land data assimilation, that encompassed a large suite of soil moisture, snow depth, snow cover, and irrigation intensity environmental data records (EDRs) from the Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave Imager (SSM/I), Advanced Scatterometer (ASCAT), Moderate-Resolution Imaging Spectroradiometer (MODIS), Advanced Microwave Scanning Radiometer (AMSR-E and AMSR2), Soil Moisture Ocean Salinity (SMOS) mission, and Soil Moisture Active Passive (SMAP) mission. The analysis indicated that multivariate assimilation provides systematic improvements in simulated soil moisture and snow depth, with marginal effects on the accuracy of simulated streamflow and evapotranspiration. An important conclusion was that across all evaluated variables, assimilation of data from increasingly more modern sensors produces more skillful results than assimilation of data from older sensors. The evaluation also indicates the high skill of National Climate Assessment (NCA)-LDAS when compared with other LSM products. Further, drought indicators based on NCA-LDAS output suggested a trend of longer and more severe droughts over parts of the western United States during 1979–2015, particularly in the southwestern United States, consistent with the trends from the U.S. Drought Monitor, albeit for a shorter 2000–15 time period.

Arsenault *et al.* (2018: *Geosci. Model Dev.*) described the development of the Land surface Data Toolkit (LDT), which is an integrated framework designed specifically for processing input data to execute LSMs and hydrological models. LDT not only serves as a preprocessor to the NASA Land Information System (LIS), which is an integrated framework designed for multi-model LSM simulations and data assimilation (DA) integrations, but also as a land-surface-based observation and DA input processor. It offers a variety of user options and inputs to processing datasets for use within LIS and stand-alone models. The latest public release of LDT is available at: https://lis.gsfc.nasa.gov/releases.

The second phase of the North American Land Data Assimilation System (NLDAS-2) was operationally implemented at NOAA/NCEP as part of the production suite in August 2014. Xia *et al*, (2019: *Journal of Hydrometeorology*) described the Variable Infiltration Capacity (VIC) model as one of the four land surface models of the NLDAS system. Their investigation evaluated VIC403 and VIC412 as part of a comprehensive assessment that targeted multiple variables and used multiple metrics to assess the performance of different model versions. Their evaluation showed that there was a large and significant improvements in VIC412 over the southeastern United States when compared with VIC403 and VIC405. Overall, the model upgrade enhanced model performance and skill scores for most parts of the continental United States; exceptions included the Great Planes and western mountainous regions, which suggests that VIC model development is on the right path.

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. Water quality activities related to coastal process and ecosystems are highlighted in the Carbon Cycle and Ecosystems Focus Area Section.

Strategic Development and Community Engagement

The WEC Focus Area continues to work with agency partners, the terrestrial hydrology and energy cycle research communities, and other stakeholders to identify and advance key science objectives and promote awareness of the program.

WEC will be hosting a SnowEx workshop in September 2019. The workshop will opportunity to share results based on the SnowEx2017 field campaign along with other

NASA (and non-NASA) sponsored research, including modeling and assimilation studies. The goal of the workshop is to leverage these results to highlight and refine "gap" areas in our understanding and abilities of snow remote sensing algorithms, as identified in the SnowEx science plan. Discussions will focus in on specific plans for future field campaigns (2020-2023) that will shore up our deficiencies.

One such gap is understanding the abilities of L-band SAR to resolve snowpack properties over a longer period of snowpack evolution. This will be addressed by SnowEx2019-20, during with the NASA UAVSAR will be deployed bi-weekly over up to thirteen field sites in the Western US, from December 2019 through May 2020. The sites represent the range in snow-types and offer robust testing of our L-band SAR related algorithms. The cadence of deployment also mimics the future NISAR satellite, providing information on what contribution that satellite will be able to make to assessing Snowpack properties. A second component of SnowEx2019-20 will again be done over the Grand Mesa (Colorado) using the NASA SWESARR instrument. The multiple wavelength, and active and passive capabilities, of the sensors will provide new data to test our multi-channel algorithms.

NASA will also contribute the SLAP (Soil Moisture, L-band Active Passive) sensor to LIASE, a two-week field campaign occurring in the summer of 2020. This international effort occurring in Northern Spain address the need for more co-observation of different components of land-atmosphere interaction. Detailed, high-resolution observations of the soil moisture field, collected by SLAP, will offer new insight into the spatial specifics of boundary layer development.

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FY 2019 Annual Performance Indicator	FY 16	FY17	FY18	FY19
ES-19-7: 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-19-9: 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 multidecadal time scales, by focusing on the individual and interactive climate processes occurring in the ocean, atmosphere, land and ice. Through a wide range of disciplinary and interdisciplinary projects, CVC supports the evaluation and utilization of satellite, aircraft and ground-based observations of the global ocean, sea and land-based ice, land surface and atmosphere, as well as their integration into comprehensive, interactive Earth system models and assimilation systems. Highlights of results published this past year are summarized herein under seven major sections, as follows:

- Sea Ice in the Climate System
- Land Ice in the Climate System
- Oceans in the Climate System
- Ocean-Atmosphere Interactions
- Ocean-Hydrology Interactions
- Ocean interface with the Earth System
- Earth System Modeling

Sea Ice in the Climate 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. NASA continues to study sea ice and its interactions with other components of the Earth System using a number of space-based measurements.

Update on sea ice extent

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 the support of researchers that contribute to NOAA's Arctic Report Card (http://www.arctic.noaa.gov/Report-Card). The ASINA website continues to be a primary reference for researchers, the media, and the general public. This year ASINA reported that the Arctic minimum sea ice extent occurred in September, 2018 and was the sixth lowest on record at 4.71 million square kilometers while the maximum sea ice extent occurred in March, 2019 and was the seventh lowest on record at 14.78 million square kilometers. As of July, 2019, Arctic sea ice loss rates are tracking those recorded in 2012, the year that saw the lowest September sea ice extent.

Two papers came out that put the long-term changes in Arctic and Antarctic sea ice into perspective. The first, Kwok (2018), extended the Arctic sea ice thickness, volume, and multiyear ice records by comparing the pre-satellite submarine data from 1958 – 1976 to the recent Cryosat-2 measurements from 2011 – 2018. They find that sea ice thickness at the end of the melt season decreased by 66% over the six-decade period. Between 1999 - 2017, multiyear ice cover has decreased by 50% and now covers less than one third of the Arctic Ocean. The study concludes that as much of the multiyear ice is lost, variations in sea ice thickness and volume will be controlled by the changes in seasonal ice, will be more moderate, and will be more sensitive to climate forcing.

The second paper by Parkinson (2019) put the long-term changes in Antarctic sea ice in perspective using a 40-year record of sea ice extent from passive microwave satellite observations. The study highlights the dramatic reversal in Antarctic sea ice extent trends seen from 2014 to 2017. Prior to 2014, Antarctic sea ice extent had substantial interannual variability but an overall small positive trend. From 2014 to 2017, Antarctic sea ice extent decreased to record low values and a minimum was reached in 2017. The rate of change during the four-year period exceed the rate of change in any other four-year period from 1978 to 2018 in either the Arctic or the Southern Ocean.

Characterizing sea ice properties

Characterizing and modeling snow on sea ice continues to be an important research topic both in terms of understanding the complex Earth System interactions in the Arctic and the Southern Ocean and for interpreting ICESat-2 altimetry measurements over the sea ice. Webster et al. (2018) highlighted the current state of knowledge regarding snow on sea ice including the key differences between how snow on sea ice evolves in the Arctic and Antarctic. They identify two key challenges that need to be addressed: 1) obtaining better observations of snow processes and properties including depth, albedo, and density and 2) determining what characteristics and processes are critical to reproduce in models to make accurate projections. Efforts to measure and monitor snow basin-wide using unmanned aircraft and through synthesis of altimeter data from ICESat-2 (which measures the snow-air interface) and Cryosat-2 (which measures the ice-snow interface) was encouraged, along with process-oriented observations designed and executed jointly by the modeling and observational communities.

To advance the modeling aspect, a new, open source snow on sea ice model was introduced which produces daily estimates of snow depth and density across the Arctic during the accumulation season (Petty et al. 2018). The NASA Eulerian Snow On Sea Ice Model (NESOSIM) joins the ranks of other models of varying complexity currently used to estimate snow on sea ice. The main goal of NESOSIM is to produce reliable basin-scale estimates of daily snow depth and density that will be useful in interpreting satellite altimetry measurements of sea ice thickness. The model is forced with winds and snowfall from reanalysis, sea ice drift from satellite measurements, and sea ice concentration from passive microwave measurements. Initial comparisons between NESOSIM and Operation IceBridge (OIB) snow radar data and in situ snow depth measurements indicate good agreement in terms of the seasonal cycle of snow depth and density and good agreement with regional snow depth estimates.

Other studies focused on improving our ability to characterize other sea ice properties from space or airborne platforms. One example looks at estimating sea ice pressure ridge sail height from high resolution Digital Mapping System (DMS) imagery collected during OIB campaigns in the Arctic (Duncan et al. 2018). This study demonstrates the ability to estimate sail height from DMS images and suggests the technique could be applied to the full collection of imagery to develop a database of sail heights in the Arctic basin. Sea ice sail height is a dominant topographical surface feature, and is important for estimating total sea ice mass and for modeling sea ice dynamics.

Another example from Zhang et al. (2018) updates the way melt ponds are represented in the Marginal Ice Zone Modeling and Assimilation System (MIZMAS) model and uses MODIS observations to calibrate and assess the model performance. Because melt ponds have lower albedo and absorb more incoming solar energy they impact the characteristics of the sea ice and also the water column beneath. This study highlights the importance of incorporating melt ponds into climate models and operational forecasts and advances the effort by adding a new melt pond distribution equation to the MIZMAS and, using satellite observations, calibrates and compares to observations from 1979-2016. They find that melt pond volume, rather than area, is more directly related to the energy budget, but that this is not yet represented in models.

Quantifying connections between sea ice and the ocean and atmosphere

Precipitation in the arctic is critical for understanding freshwater inputs to the ocean, energy budgets, and sea ice development, but poorly constrained by observations. A new study compares precipitation estimates from eight different reanalysis products from 2000 to 2016 (Boisvert et al. 2018). The team finds that the magnitude, frequency, and phase of the precipitation varies drastically between reanalysis products but that the interannual variability is similar. Specifically, all precipitation products predict more frequent precipitation compared to observations. Three models, ERA-Interim, MERRA, and NCEP R2, produce precipitation events that compare well in magnitude and timing with observations, while two, MERRA-2 and CFSR, produce precipitation magnitudes that are too large. Improving reanalysis products is key to modeling sea ice, particularly snow on sea ice, and the team suggests better representations of the Arctic atmosphere in terms of boundary layer processes, vertical motions, cloud type, and cloud microphysics.

Liu and Schweiger (2019) examine how conditions near the sea ice edge influence both the surface winds in this region as well as the low-level jet associated with the thermal boundary between the warmer ocean and the cooler sea ice. The study uses a combination of dropsonde observations and Polar Weather Research and Forecast simulations to set-up several test cases and examine the mechanisms responsible for creating a low-level jet near the sea ice edge. The team finds the mechanisms by which the temperature contrast at the surface affects the wind maximum associated with the low-level jet is different than the mechanisms that creates the wind maximum at the surface. Low-level jets in the

Arctic are more heavily influenced by the interactions between the Arctic anticyclones and approaching cyclones and the impact of the sea ice-ocean boundary is to create a large-scale, long-term pattern rather than have a local effect. The surface winds, however, are more directly affected by the thermal contrast at the sea-ice front.

Another paper looks at the intermodal spreads in the magnitude of the Arctic Amplification in CMIP5 models concluding that the mechanisms driving the model differences operate at regional scales and involve atmosphere-ocean-sea ice interactions (Boeke and Taylor, 2018). Areas of sea ice retreat are particularly important, as is the combined sea ice albedo and ice insulation feedbacks, in explaining the inter-model spread. The team finds that models that are better at widely dispersing the energy drawn from the surface in sea ice retreat regions warm more and that local atmosphere-sea ice-ocean mechanisms that occur in the sea ice retreat region are an import factor in intermodal spread.

Land Ice in the Climate System

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.

The legacy of the GRACE mission and its impact on ice sheet and glacier mass balance estimates during its 15-year lifetime from 2002-2017 are highlighted by Tapley et al. (2019). GRACE has proven to be a key tool when estimating changes in the ice sheets as it is the only direct measure of changes in mass. The footprint of GRACE allows detection of regional changes which indicates mass loss along the entire perimeter of Greenland and loss focused along the Amundsen Sea Embayment in Antarctica. During the GRACE period, Greenland measured an average mass loss of -258 ±26 Gt yr^{-1} while Antarctica measured an average mass loss of -137 ±41 Gt yr^{-1}. GRACE also allowed monitoring of interannual variability in mass loss from the ice sheets and estimates of mass change trends in areas outside the poles.

Two papers reconstruct the mass balance of the Greenland Ice Sheet (Mouginot et al. 2019) and the Antarctic Ice Sheet (Rignot et al. 2019) using the mass balance method of estimating mass loss from the ice sheets. This method uses thickness, surface elevation, ice velocity, and surface mass balance to calculate how much ice is being lost. Advantages of this method are that it allows partitioning between different process responsible for mass loss the ability to extend the estimate further into the past using Landsat images to estimate glacier fluxes. Mouginot et al. (2019) reconstruct the mass balance of the Greenland Ice Sheet over the 46-year period from 1972 to 2018 finding that, since the 1980s, mass loss has increased six-fold as the mass balance began to deviate from its natural range of variability. The study concludes that Greenland has contributed 13.7 mm of sea level rise since 1972 with more than half coming in the last 8 years. Rignot et al. (2019) reconstruct the mass balance of the Antarctic Ice Sheet over the 40-year period from 1979 to 2017. Mass loss from the continent grew from 40 ±9 Gt

yr^{-1} in 1979-1990 to 252 ±26 Gt yr^{-1} in 2009-2017 and was concentrated in areas near warm, salty, subsurface, circumpolar deep water where the conditions caused enhanced glacier flow. The study predicts that this trend will continue as more circumpolar deep water is transported toward these regions due to enhanced polar westerlies.

Ice sheet interactions in the Earth System

Several studies made advances in understanding how other components of the Earth system impact ice sheets. Using a newly created 200-year snow accumulation reconstruction, Medley and Thomas (2018) find that increased snowfall over Antarctica in the 20th century mitigated approximately 10 mm of sea level rise during that time period. The study uses 52 annually resolved ice cores of snow accumulation along with modeled spatial signatures from atmospheric reanalysis to reconstruct snow accumulation from 1801 to 2000. The study explored possible links to large-scale atmospheric dynamics (the Southern Annular Mode) and atmospheric warming.

Larour et al. (2019) demonstrates another mitigation factor important for estimating future sea level rise by looking at the relatively short-term (500 year) impacts that elastic uplift and self-attraction and loading can have on glacier retreat. This study modeled these effects at a higher-resolution (kilometer scale) to capture the impact they would have on the fast retreating Thwaites Glacier in West Antarctica. The study concludes that the sea level contribution from Thwaites Glacier will be reduced by 26.8% and grounding line retreat reduction of 38% by 2350 compared to a modeling experiment that does not include these solid earth feedbacks.

The importance of warm and salty circumpolar deep water (CDW) in determining glacier retreat is highlighted in Milillo et al. (2019). Recent InSAR observations at high temporal resolution at Thwaites Glacier show glacier flow and grounding line characteristics in detail. Results show faster migration in a region with a prograde bed elevation and slower migration in an area with a retrograde bed. These results were unexpected given previous understanding of bed topography impacts on glacier thinning and retreat. However, the team argues that the differences can be explained by the formation of subglacial channels and cavities that allow CDW to drive changes in glacier flow. The study notes that the complexities of ice-ocean interactions highlighted by their findings, are not currently represented in coupled ice sheet-ocean models.

Ice sheet processes

A study examining the choice of basal friction treatment in ice sheet models found that using regularized Coulomb friction instead of the more commonly used power law friction provided better model-data agreement, suggesting that adapting such friction laws could improve estimates of future sea level (Joughin et al. 2019). The team chose Pine Island Glacier as a 'natural laboratory' where observations of glacier velocity and geometry exist from 2002 to 2017. They find that the using regularized Coulomb friction laws allows for the effect of cavitation on sliding and can reproduce glacier behavior over both hard bedrock and weak till. The study suggest that more ice-sheet models used for sea-level projections should adopt this type of friction law.

Ice sheet surface mass balance and sub- and supraglacial water

Understanding the origin and fate of surface melt water in Greenland continues to be an important topic and advances in the past year have produced a better understanding of controls on surface melt (Ryan et al. 2019), how surface melt is delivered to the bed (Poinar et al. 2019), and new methods for detecting firn aquifers (Chu et al. 2018).

A study by Ryan et al. (2019) finds that shifting snowlines on the Greenland Ice Sheet caused enhanced surface melt by exposing bare ice, which is darker, and changing the albedo in the ablation zone. They tracked shifting snowlines using MODIS satellite imagery and compared it to regional climate models finding that models do not sufficiently capture the role of the snowline-albedo feedback adding uncertainty to the estimate of bare ice exposure which is a primary control for surface melt.

Understanding what happens to surface meltwater is the focus of Poinar et al. (2019). The team uses a subglacial hydrological model to test how firn aquifers can delay the transport of surface meltwater to the bed. They find that by adding firn aquifers to the model, seasonal variations in subglacial water pressure are dampened which may explain anomalous ice velocity patterns in Southeast Greenland. In general, the subglacial hydrologic system affects how ice flows, and understanding how that system develops and how it is affected by surface melt is critical to future projections of glacial melt.

A third study, Chu et al. (2018), uses the very high-frequency Multichannel Coherent Radar Depth Sounder 2 data that was collected from 2012 to 2014 as part of Operation IceBridge to constrain the firn aquifer thickness estimates at Helheim Glacier in Greenland. This new technique compliments earlier methods for detecting firn aquifers because it can penetrate deeper than the previous method to constrain the thickness of deeper aquifers. The team also estimates that the aquifer studied stored only half the previously estimated amount of water from 2012-2014 due to new thickness estimates, although noted that the system is highly dynamic.

Global glacier change

Looking beyond the Greenland and Antarctic Ice Sheets, several studies focused on glacier change globally. The first, Hock et al. (2019), compared projections from six global glacier models as part of the Glacier Model Intercomparison Project (GlacierMIP). Four RCP emission pathways were considered in the projections which resulted in sea level equivalent mass loss of 94 ± 25 mm for RCP2.6 and 200 ± 44 mm for RCP8.5 for glaciers outside of Greenland and Antarctica by 2100. The study found large differences in results among the six models which they attributed to different model physics, calibration procedures, downscaling procedures, input data, and initial ice volume but noted that there were recent improvements to the global glacier inventories and datasets of mass change due to advances in remote-sensing technologies.

A second study used observations from GRACE to estimate the changes in mass in the glaciers outside Greenland and Antarctica from 2002-2016 finding a mass loss rate of 199 ±32 Gt yr^{-1} which is equivalent to 8 mm of sea level rise (Wouters et al. 2019). The GRACE-based estimates agree well with *in situ* observations and altimetry-based observations in the larger regions. In the northern hemisphere, interannual variability can be explained by large scale atmospheric patterns, for example, the North Atlantic Oscillation.

Regional glacier change - Alaska

A focus on Alaska glaciers brought advances in several areas including surge dynamics (Trantow and Herzfeld 2018), glacier velocity (Altena et al. 2019), and geometric controls on glacier retreat (Enderlin et al. 2018).

Trantow and Herzfeld (2018) looked at the Bering Bagley Glacier System in Alaska to develop a method which uses crevassing characteristics to analyze ice dynamics and glacier surface structure during a glacial surge from 2011 to 2013. Surge events are not well understood but are important to characterize and model in order to predict future mass loss. The team used Landsat-7 and airborne-based data to identify crevasse characteristics and numerical modeling techniques to study the ice dynamics and surface structures during the surge. They found that their model was able to reproduce crevassing in the majority of their study area.

Another study identified changes in glacier velocity by combining glacier velocity fields from the NASA GoLIVE product, which are derived from Landsat-8 images, with an advanced data filtering and interpolation scheme that allows for automated detection of small changes in glacier velocity over a large region (Altena et al. 2019). The study demonstrated the ability to automatically detect short-term velocity variations over a large glacier area. Tools such as these will become more important as the volume of data grows, and will allow scientists to identify interesting areas for further analysis.

The third study focuses on two glaciers in Alaska, Columbia Glacier and Post Glacier, which share environmental forcing, to isolate the influence of geometry on tidewater glacier dynamics (Enderlin et al. 2018). They find that the geometry controls the long-term retreat but that environmental factors control the short-term seasonal fluctuations in flow speed and terminus position. The team suggests that models should allow for both geometric and environmental driven controls when developing calving parameterizations.

Regional Glacier Change – High Mountain Asia (HMA)

NASA’s HiMAT (High Mountain Asia Team) program entered its third and final year with the current science team. The team has contributed numerous datasets to the National Snow and Ice Data Center HiMAT repository (https://nsidc.org/data/highmountainasia) and recent results include an overview of accelerated ice loss across HMA over the past 40 years (Maurer et al. 2019) and a study isolating controls on glacier melt (Bushan et al. 2018).

Maurer et al. (2019) compare glacier ice thickness from two time periods, 2000-2016 and 1975-2000, to estimate ice loss across the Himalayas over the past 40 years. The team uses digital elevation models created from both cold war-era spy satellite film and modern stereo satellite imagery to span the timeframe. They find that the rates of ice loss are constant along the 2000-km transect, and that the mass loss rate doubled from -0.22 ± 0.13 m w.e. yr^{-1} in 1975-2000 to -0.43 ± 0.14 m w.e. yr^{-1} in 2000-2016. Clean-ice, debris-covered, and lake-terminating glaciers all had the same acceleration in mass loss suggesting that the responsible forcing would need to explain the change in all glacier types across the region. The team concludes that the loss trend is consistent with weather station air temperature data in the region and that accurately quantifying glacier response to air temperature changes in degree-day and energy balance models would improve future projections of mass loss in HMA.

Bushan et al. (2018) focuses on glaciers in the Zanskar Basin in Western Himalaya to quantify mass budget and surface velocity. They also compare clean-ice to debris covered ice, as well as looking at differences due to glacier hypsometry and orientation. They also find that debris-covered and clean-ice glaciers have similar ice loss rates although the two glacier types display different patterns of melt. For example, melt typically is at a maximum closer to the terminus of a glacier in clean-ice cases while maximum melt occurs further upstream when the glacier is extensively debris-covered among other key dynamical differences.

Oceans in the Climate System

Oceans play a fundamental role in the Earth's system, modulating our planet's climate and weather by storing and transporting large quantities of heat, water, moisture, 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 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 2018-2019 advancing our understanding of the ocean's role in the climate system.

Ocean dynamics drives heat redistribution

Oceans have an important role in the Earth's energy imbalance. Due to its large heat capacity, which exceeds that of the atmosphere over 1000 times, the oceans have absorbed most of the heat gained by the planet in response to anthropogenic greenhouse gas emissions, leading to thermal expansion and sea level rise. Our ability to predict the future anthropogenic warming critically depends on accurate estimates of past ocean content change. However, before the 1990s, most ocean temperature measurements were above 700 m and thus insufficient for an accurate global estimate of ocean warming. The study by Zanna et al. (2019) combines historical temperature measurements with the interior ocean transports from NASA ECCO (Estimating the Circulation and Climate of the Ocean) framework to present a reconstruction of ocean heat over the past 150 years, with global coverage of the full ocean depth. The results reveal ocean warming of 436 1021 J since 1871. For comparison, the excess heat stored in the ocean due to anthropogenic greenhouse emissions is about 1000 times as great as the amount of energy humans use each year, globally. In addition, Zanna et al. (2019) demonstrate that changes in heat transport by ocean circulation have produced significant regional variations in ocean heat content, and consequently, sea level rise, confirming the active role of ocean dynamics in driving climate variability.

One of the mechanisms by which the oceans control the planetary heat budget is through the meridional thermohaline circulation. The Atlantic branch of this meridional circulation plays an important role in global climate variability, and the concerns for its potential slowdown has led to multiple research efforts to measure and understand its strength and evolution. A recent study by Li et al. (2019) makes progress in our understanding of the structure and interaction between the various components of the Atlantic meridional overturning circulation. Analysis of direct observations from the Argo and RAPID arrays and ocean/ice models, including NASA GISS, suggest potential coherence between the strength of Labrador Sea water formation and the meridional transport. This linkage can explain the weakening of the meridional circulation, when the formation of deep water in Labrador Sea was suppressed in response to an increase in freshwater under a warming climate.

Ocean mixing is linked to climate variability

Besides redistribution of heat, another way that oceans affect the Earth’s climate involves the mixing of heat anomalies throughout the water column, which generally slows down the rate of surface warming. Mixing can be performed by small-scale ocean processes, such as convection, diapycnal and isopycnal diffusion, mesoscale and submesoscale eddies.

Busecke and Abernathey (2019) explore ocean mixing on scales of 50-200 km and its linkages with climate variability. Using satellite-derived ocean velocities from NASA altimetry missions, Busecke and Abernathey (2019) reconstruct the first time-resolved global datasets of lateral mesoscale eddy diffusivities - the rates at which mixing processes transport tracers and that are used in coarse-resolution climate models to represent unresolved trans- ports. They discover that mixing rates in the ocean vary on inter-annual and longer timescales, including changes associated with ENSO, NAO, and PDO. The evidence suggests that mesoscale mixing could be an important cli- mate feedback mechanism: a coupling between large-scale climate variability and eddy mixing rates occurring due to small-amplitude changes in the large-scale flow. The results could have far-reaching consequences for the Earth System Modeling community, which can potentially improve model biases of internal variability and long-term trends in ocean circulation, water formation, and redistribution of heat, salt, and carbon.

Mixing by smaller-scale processes, less than 50 km or submesoscale, has been receiving significant attention given the upcoming launch of the SWOT mission. Submesoscale processes are order one Rossby numbers, representing a transition between the largely-balanced mesoscale and the unbalanced gravity wave scales. Despite growing evidence of their significant contribution to the vertical exchange of properties, submesoscale processes are not captured in climate models. Su et al. (2018) make a major advance towards realizing this challenge by using a novel global ocean simulation MITgcm in ECCO configuration with 2-km horizontal resolution that for the first time globally resolves the ocean submesoscale heat transport at the 10-50km scales. They conclude that submesoscale turbulence produces a large and systematically upward heat transport globally throughout the upper ocean. For example, the winter-time averages can reach up to 100 W/m2 in mid-latitudes, which is five times larger than mesoscale heat transport. This submesoscale heat transport warms the sea surface up to 0.3 °C, producing an upward air-sea heat flux of 4-10 W/m2 that is comparable to climatological air-sea heat fluxes.

Submesoscale structures are produced by several classes of frontal instabilities, which tend to intensify during winter when the mixed layer is the deepest. Callies and Ferrari (2018) explore the nature of baroclinic instability in the mixed layer, quantifying its strength in the presence of convection. By employing numerical simulations using MITgcm, they demonstrate that baroclinic instabilities can be remarkably resilient to the presence of convec- tion. This suggests that despite the vigorous atmospherically-forced turbulence in winter mixed layers, baroclinic instabilities can persistently grow, generate balanced submesoscale turbulence, and modify the bulk properties of the upper ocean, such as heat, salt, nutrients, oxygen, and dissolved gasses.

Oceans control melting rates of land ice

An increasing amount of evidence from NASA Oceans Melting Greenland (OMG) campaign suggests a leading role of ocean dynamics and thermodynamics in controlling the fate of the adjacent land ice complexes. OMG studies suggest the vigorous entrainment of warmer subsurface waters around Greenland causes accelerated mass loss, thinning, and glacier retreat (Willis et al., 2018; Wood et al., 2018). This ice/ocean coupling is further supported by the modeling studies in the first fully-synchronous, coupled ice shelf-ocean model by (Jordan et al., 2018) in MITgcm/ECCO configuration. They achieved a synchronous ice/ocean coupling through continuously updating the ice-shelf thickness, while conserving ocean heat, salt, and mass, and demonstrate how raising the pycnocline leads to a reduction in both ice-shelf mass and back stress, and hence buttressing.

Similar ocean/ice coupling is observed in Antarctica, showing how melting of the West Antarctic ice shelves is enhanced by the warming waters of the Circumpolar Deep Water that intrude onto the continental shelf of the Amundsen and Bellingshausen Seas. Using new ECCO ocean/ice coupling, Nakayama et al. (2018) shows that ocean circulation controls the pathways of the Circumpolar Deep Water and thus affect the shelf properties, including the retreat of West Antarctic glaciers.

While the effect of warmer waters on accelerated mass loss has been observed in the past, a new study by NASA OMG scientists Khazendar et al. (2019) suggests that the direct ocean/ice relationship holds when the oceans are cooling as well. Over the past twenty years, Jakobshavn Isbrae has thinned by more than 100 meters, and has been Greenland's single largest source of mass loss to the ocean. Ocean warming has been suspected of initiating the glacier's retreat, acceleration, and thinking in the late 1990s. However, in 2016 and 2017 NASA OMG observations showed that Jakobshabn slowed and thickened, as detected by GLISTIN and ATM surface elevation data. Using OMG temperature observations and ECCO budget analysis, Khazendar et al. (2019) linked the glacier thickening to large-scale ocean cooling. The new ocean-ice coupling has important implications for projecting future changes of sea level that need to account for ocean variability, ocean-induced melting, and dynamic coupling between the ocean and cryosphere.

Ocean-Atmosphere Interactions

The ocean, through latent and sensible fluxes, supplies heat and moisture to the atmosphere that powers the winds that, in turn, generate wind-driven ocean motions and drive the exchange of momentum, heat, and water vapor at the air-sea interface. A strong air-sea coupling is particularly prominent in the tropical and equatorial ocean regions where the oceans exert a strong feedback on atmospheric motions and produce coupled ocean-atmospheric modes of climate variability, such as ENSO, PDO, and MJO that are often linked to weather anomalies on land. Understanding and predicting these climate modes is one of the priorities for NASA and involves improved understanding of ocean-atmospheric coupling, enhancing our existing tools, and exploring novel approaches in air-sea exchange monitoring.

Air-sea coupling through ocean winds and currents

Lee et al. (2019) used a suite of satellite ocean and atmospheric observations to study the linkage between the ocean currents and air-sea fluxes in the climatically important maritime continent. The study discovered that monsoon- induced precipitation (and consequently runoff) in the maritime continent plays a crucial role in regulating the seasonal strength of a key element of the global ocean circulation system - the Indonesian Throughflow, which links the Pacific and Indian Oceans. The finding has significant implications to the downstream effects of the Indonesian Throughflow, including its impacts on Indo-Pacific climate and weather as well as marine biogeochemistry and carbon cycle on longer time scales.

Kilpatrick et al. (2018) used NASA's scatterometer and other observations to reveal an upwelling hot spot in the Southern California Bight, which is a highly-productive biological area. They find that the enhanced Chlorophyll feature in the Bight appears to be forced jointly by orographic winds and bathymetry, with seasonal peaks in phase with the upwelling winds winds and longer-scale variability related to remotely-forced variations in temperature. Analysis of multi-year observations suggest the hot spot of ocean productivity is driven by the ocean circulation, upwelling, and large-scale climate variations associated with ENSO and marine heat waves.

Menezes et al. (2019) used NASA satellite and in situ wind observations, as well as MERRA-2 reanalysis, to investigate intense evaporation events caused by westward wind events in the northern Red Sea, a region with one of the highest evaporation rates on Earth and a source of moisture for the arid atmosphere of the Middle East. The study shows that the occurrence of the wind events has consistently increased over the last three decades, and the colossal surface heat transferred from the sea to the atmosphere in these events occurs because the winds coming from the Arabian Desert are extremely dry. Thus, these wind events are called ”dry-air outbreaks”, in analogy to the ”cold-air outbreaks” that cause extreme evaporation events off of the coast of the northeastern US when strong winds bring cold, dry air over the warm Atlantic Ocean. The study also reveals that the dry-air outbreaks in the Red Sea are very likely to be connected with the wintertime Shamal winds that cause intense sandstorms in the Persian Gulf. These outbreaks may have far-reaching impacts in both the atmosphere and ocean since evaporation is a source of moisture for the atmosphere and also control the formation of the Red Sea Overflow Water that spreads throughout the Indian Ocean and beyond.

Ocean salinity as an indicator of air-sea coupling

NASA salinity remote sensing continues to improve our knowledge of air-sea interaction. Originated with Aquarius and continued with SMAP, NASA probing of the top cm of the sea surface salinities provides a unique monitoring capability for the interfacial exchanges of water between the atmosphere and the upper-ocean. In addition, observing salinity from space offers the advantages of global coverage and the ability to capture space and time scales not afforded by in situ platforms.

The high temporal resolution of satellite surface salinity enabled a better understanding of large-scale intra- seasonal phenomena, such as the Madden-Julian Oscillation (MJO), which is the dominant climate mode at sub-seasonal time scales in the tropics that impacts the global weather and climate. Subrahmanyam et al. (2018) used SMAP satellite salinity observations to detect the existence of 30- to 90-day period intra-seasonal oscillations in Bay of Bengal associated with MJO and the associated impacts on surface density variations, emphasizing the role of upper-ocean dynamics in regulating MJO. The ability to detect such oscillations in salinity data will have direct bearing on our ability to understand and model the air-sea interaction processes, including development and intensification of weather disturbances.

Hasson et al. (2018) demonstrated the utility of satellite salinity data to improve our understanding of ENSO and ENSO-related precipitation. By analyzing NASA and ESA satellite salinity data, Hasson et al. (2018) established a relationship between the large-scale fresh pools in the tropical Pacific with ENSO-induced precipitation and oceanic transport associated with mesoscale eddies. The examples of the linkages of satellite salinity with climate modes of variability, such as ENSO and MJO, demonstrate the potential of satellite salinity measurements to improve the representation of climate variability in ocean models and related forecasts, e.g., through assimilation of satellite salinity data into general circulation and coupled models.

Another example of the utility of salinity data to describe the ocean-atmospheric interaction is through the underlying link between the rain events and freshening of the ocean's surface. Rain falling on the ocean produces layers of low-salinity water near the surface. These ”fresh layers” are important because they enhance the coupling between the ocean and the atmosphere: for instance, they can trap solar radiation, leading to warmer sea surface temperatures. Until recently, only a handful of fresh layers had been observed due to the extreme difficulty of making measurements near the ocean surface. During the second Salinity Processes in the Upper Ocean Regional Study (SPURS-2), a novel ”Surface Salinity Profiler” captured the salinity structure of 35 rain events, providing new insight into the generation and evolution of fresh layers. These measurements led to the development of a relationship allowing scientists to predict the salinity signal generated by rainfall, as described in a new paper by Drushka et al. (2019).

Ocean-Hydrology Interactions

In addition to climate variability, ocean salinity is emerging as a robust proxy to study ocean-land linkages and the Earth water cycle. Due to its dominance in the global water cycle and the ultimate source of all rainfall and terrestrial water, the ocean provides best evidence of the ongoing intensification of the global hydrological cycle, including trends in ocean salinities.

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, draught, 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. Liu et al. (2018) demonstrated that variations in surface salinity can be used to predict rainfall on land. By correlating fall salinities with winter precipitation in the southwestern United States, Liu et al. (2018) constructed a salinity-based model of land precipitation, ranking salinity as the most important predictor compared to the other climate indices, including temperature.

NASA salinity science team continues providing new evidence of the importance and utility of satellite salinity to study ocean-land linkages (Vazquez-Cuervo et al., 2018), to determine the fate of riverine water and river plumes (Dzwonkowski et al., 2018), to monitor coastal dynamics (Grodsky et al., 2018b,a), and to constrain Arctic freshwater budget (Tang et al., 2018).

Ocean interface with the Earth System

Significant progress in understanding the multi-disciplinary interactions within the complex ocean-atmosphere-land-solid Earth system has been made in the last year. The highlights from three main areas - sea level change, ocean tides, and ocean state estimation for climate research - are provided below.

Sea level change

As a multi-disciplinary collaboration among oceanographers, glaciologists, geodesists, and hydrologists through Sea Level Change Science Team (N-SLCT), NASA has been conducting sea level science by collecting and analyzing observational evidence of sea level change, quantifying the underlying causes and driving mechanisms, producing projections of future changes in sea level, as well as communicating NASA's latest discoveries to the public through NASA's Sea Level Portal at https://sealevel.nasa.gov. As a result, progress has been made on a number of important problems in sea level science.

Fasullo and Nerem (2018) analyzed direct measurements of sea level change from satellite radar altimetry from TOPEX/Poseidon, Jason-1, 2, and 3 and concluded that the satellite altimetry begin to show ocean's response to forced anthropogenic forcing. While the regional patterns of sea level rise have been observed from satellites since 1993, it was unknown whether such patterns are temporary attributed to natural climate variations, or persistent in response to external climate forcing. In this study, Fasullo and Nerem (2018) contributed to the debate whether relatively short satellite data can reveal secular sea level rise or whether it is overwhelmed by the internal stochastic noise of the climate system. With the aid of climate models, they conclude that the observed altimeter-era patterns of sea level rise are anthropogenically-driven and thus may persist for decades to come as climate change progresses.

To provide further insights into sea level trends driven by internal climate variability, Hamlington et al. (2019) use a combination of satellite altimeters, GRACE satellites, and Argo floats to examine to which extent internal variability on timescales from intra-seasonal to decadal can be separated from long-term trends that are expected to continue into the future. The results can have important implications for developing projections of future regional sea level rise, currently pursued by N-SLCT.

Ocean tides

With 2019 celebrations of NASA Apollo's 50th Anniversary and announced Artemis Lunar Program, we highlight recent discoveries in Moon/Earth connection, focusing on ocean tides.

The connection between the Earth and Moon is through gravitation, which, as it varies with distance, creates a tidal force that causes tides, both in the ocean and the solid earth. Predicting the tidal force and ocean’s response present certain challenges, as the force depends on the details of the moon’s declination, distance, and other variations of the orbit; and the ocean’s response is complicated by the shape of the continents and variable depth. A new class of models that predict the ocean's response to tides under state-of-the-art tidal force is described in Arbic et al. (2018). This new class of high-resolution global models is forced simultaneously by tidal forcing and atmospheric fields, and can resolve a rich spectrum of internal gravity waves and tides. These new modeling capabilities provide valuable information on ocean’s circulation under realistic tidal forcing, and is suitable for a range of applications, ranging from operational purposes using the US Navy HYCOM system to climate research using NASA's ECCO Ames simulations.

Ocean tides create visible, periodic rise and fall of sea level at the coast, which can be adequately measured using NASA altimetry missions. Another way for tides to manifest is through the periodic movement of water under the ocean surface, which can create large internal displacements by hundreds of meters. At the surface, this displacements are only a few cm, but can also be detected by satellite altimeter missions, albeit with some challenges. New study by Zaron (2019) demonstrates that improved tidal predictions can be achieved by accounting for the tidal currents under the ocean surface. The novel aspect of his methods is a combination of the satellite data with ocean in situ measurements from drifting buoys. This combination of data provides insight into how much the ocean is mixed by tides, and, with more data in the future (including SWOT), it will provide information to improve climate model representation of ocean tidal mixing.

The complicated shape of the continents and varying ocean’s depth creates a variety of tides across the global ocean. Tides of amplified magnitudes, or high tides, are known to cause local flooding, often referred to ”nuisance” or ”clear-sky” flooding, leading to public inconveniences such as road closure or an adjustment to the normal daily routine. While not catastrophic on its own, in many locations flooding associated with high tides is a chronic problem, potentially leading to significant damage to coastal infrastructure. In the past, high tide flooding has typically occurred in low-lying coastal areas. Today, with the ongoing increase of relative sea level, high-tide flooding is occurring more frequently and with increasing severity. A recent study by Burgos et al. (2018) showed that nuisance flooding has increased 325% since 1960 in Norfolk, VA and is becoming more prominent. If further combined with naturally-occuring inter-annual and decadal variability, the impact of future high-tide flooding will be even more dramatic. The analysis shows that this flooding will continue to increase in frequency with time and by 2050 can produce over 200 floods events a year, or almost daily occurrence.

Ocean state estimates for climate research

Another inter-disciplinary area of research is the production of the best possible estimates of the ocean state that can be used to assess the ocean’s role in climate system, including the changes in the atmosphere, cryospheric changes, land hydrology, and solid Earth dynamics. NASA continues supporting the development of the ECCO framework that integrates nearly all existing ocean observations under the constraints of the conservation laws of physics and provides a description of the ocean circulation over the past two decades, as well as the evolution of sea ice and changes in the ocean biogeochemistry (Fukumori et al., 2018).

Due to its dynamical consistency and adjoint capabilities, ECCO continues to be a flagship ocean reanalysis (Wunsch, 2018), supporting a range of applications in climate research, including ocean heat content (Zanna et al., 2019), sea level, global overturning and abyssal circulation (Cessi , 2019), ocean angular momentum (Quinn et al., 2018), and ocean-ice coupling (Wood et al., 2018; Jordan et al., 2018; Nakayama et al., 2018; Khazendar et al., 2019).

ECCO's ability to perform high-resolution nature runs as well as versatile adjoint capabilities allows one to assess the design and exploration of optimal ocean observing system networks, also known as Observing System Simulation Experiments (OSSEs). Wang et al. (2018) used ECCO for OSSEs studies of the upcoming SWOT missions, identifying the suitable oceanographic in situ measurements to perform the mission calibration and validation. As an OSSEs tool, ECCO machinery offers both traditional (i.e., data assimilation versus control run) evaluations, as well as more versatile, adjoint sensitivity experiments that provide insight into where and when observations are most needed.

Earth System Modeling

Models supported by the Modeling, Analysis and Prediction (MAP) program within the Climate Variability and Change focus area include, but are not limited to the following:

- 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.
- The Estimating the Climate and Circulation of the Ocean (ECCO) assimilation system, jointly supported by the Physical Oceanography and MAP components of the CVC focus area. Its goal is to generate an accurate, high resolution, coupled ocean/sea ice/biogeochemistry atmospherically-consistent state estimate for research applications and prediction.

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

Climate Modeling Advances

Appropriate representation and prediction of climate extremes is an important current priority for the CVC focus area. Blocking anticyclones are an important cause of extreme heat events at midlatitudes. Their improved representation in climate models depends on improved understanding of the observed relationship between blocking anticyclones and surface extremes. However, there is no consensus on the definition of blocking anticyclones, and several indices have been developed to measure them. Chan et al. [2019] linearly regressed interannual variations of hemispheric continental summer surface hot extreme area on the corresponding variations of blocking anticyclones in the ERA-Interim reanalysis data and used cross-validation test error to measure the blocking-extreme link. This helps to quantify the association of hot extremes and blocks with an uncertainty estimate and can be used for other extremes as well.

Lim et al. [2018] studied the role of climate change and variability on the 2017 Atlantic hurricane season, which was extremely active with six major hurricanes. Sea surface temperatures over the eastern main development region (EDMR) were the warmest on record. ENSO, NAO, and AMM contributed to favorable wind shear conditions. Results suggest that unusually warm SST in the EDMR along with the long fetch of the resulting storms over record ocean heat content were the key factors driving the strong activity in 2017.

Santer et al. [2019] provide evidence that a human-caused signal in the seasonal cycle of tropospheric temperature has emerged from the background noise of natural variability, by comparing satellite data with the characteristic “fingerprint” of anthropogenic influence obtained from climate models. The models and observations show common large-scale changes in geographical patterns of seasonal cycle amplitude. These common features include increases in amplitude at mid-latitudes in both hemispheres, amplitude decreases at high latitudes in the Southern Hemisphere, and small changes in the tropics.

DelSole et al. [2019] investigate confidence intervals in “optimal fingerprinting,” a standard method for detecting climate changes, and dealing with the uncertainty that the response to climate forcing is not known exactly, but in practice is estimated from ensemble averages of model simulations. A bootstrap method is shown to give correct confidence intervals in both strong- and weak-signal regimes, and always produces finite confidence intervals, in contrast to the likelihood ratio method which can give unbounded intervals that do not match the actual uncertainty.

Garfinkel et al. [2018] used the GEOS Chemistry-Climate model to examine the extent of precipitation and temperature nonlinearities in the response to El Nino/La Nina phenomena. In the Central North Pacific region where the sea level pressure response to El Niño-Southern Oscillation (ENSO) peaks, nonlinearities are relatively muted. In contrast, changes to the east of this region (i.e. the far-Northeastern Pacific) and to the north of this region (over Alaska) in response to different ENSO phases are more clearly nonlinear, and become statistically robust after more than 15 events are considered. The relative prominence of these nonlinearities is related to the zonal wavenumber of the tropical precipitation response.

Clouds and Cloud Process Modeling Advances:

Low clouds are an important source of uncertainty in climate model estimates of equilibrium and transient climate sensitivity. Cesana et al. [2018] studied the low cloud cover (LCC) and cloud radiative effect (CRE) interannual changes in response to sea surface temperature (SST) forcings in the GISS model E2 and in 12 other climate models, as a function of their ability to represent the vertical structure of the cloud response to SST change against 10 years of CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) observations. The more realistic models capture the observed interannual LCC change quite well while the others largely underestimated it. Consequently, the more realistic models simulate more positive shortwave (SW) feedback than the less realistic models, in better agreement with the observations. The ability of the models to represent moist processes within the planetary boundary layer (PBL) and produce persistent stratocumulus (Sc) decks appears crucial to replicating the observed relationship between clouds, radiation and surface temperature. This relationship is different depending on the type of low clouds in the observations. Over stratocumulus regions, cloud-top height increases slightly with SST, accompanied by a large decrease in cloud fraction, whereas over trade cumulus (Cu) regions, cloud fraction decreases everywhere, to a smaller extent.

Kurowski et al. [2018] investigated the effects of cold pools driven by rain evaporation on the shallow-to-deep convection transition over land, using Large Eddy Simulation ensembles with and without cold pools, and with either interactive or prescribed surface fluxes. These simulations have implications for parameterization of cloud processes within large-scale Earth system models. Cold pools enhance near-surface temperature and moisture standard deviations as well as maxima of the near-surface updraft velocity. They also lead to the reduction of cloud lateral entrainment, deeper vertical development of the cloud layer, and a few-times-larger accumulated surface precipitation. Interactive surface fluxes provide a damping mechanism that noticeably suppresses all these effects. A potential surprise of this research is that, cold pools do not appear to significantly change the cloud-base convective mass flux that approximately follows the evolution of surface heat fluxes.

Meyers et al. [2018] analyzed a “marine heatwave” between 2013 and 2015 over the northeast Pacific Ocean, characterized by the highest surface temperatures ever recorded in a swath from near the Gulf of Alaska to off the coast of Baja California. Satellite data to show that the heatwave was associated with a record decrease in the typically high cloudiness over an area of the Pacific off Baja California that is roughly half the size of the contiguous United States. Such a deficit in cloud cover coincided with a large increase in the amount of sunlight absorbed by the ocean surface, resulting in extremely warm temperatures. Their findings suggest that a positive feedback between clouds and ocean surface temperature can strongly contribute to significant and difficult-to-predict changes in marine climate. This study provides a metric for future modeling studies of the role of clouds in the climate system.

Cesana et al. [2019] assessed the vertical distribution of radiative heating rates (RHRs) in climate models using a multimodel experiment and A-Train satellite observations, for the first time. Compared to observations, models systematically showed an excess of high-level clouds around 200 hPa in the tropics, and a general lack of mid- and low-level clouds. The excess clouds and ice water content in the upper troposphere result in excess infrared heating in the vicinity of and below the clouds as well as a lack of solar heating below the clouds. In the lower troposphere, the smaller cloud amount and the underestimation of cloud-top height is coincident with a shift of the infrared cooling to lower levels, substantially reducing the greenhouse effect. A better agreement between observed and modeled cloud profiles could substantially improve the RHR profiles.

Gettelman et al. [2019] upgraded their cloud microphysics scheme - which is incorporated in both the GISS Model E and GEOS modeling systems, by adding rimed hydrometeors (graupel or hail) to a stratiform cloud scheme for global models and tested the effects in a variety of configurations. Tests showed expected production of small amounts of rimed ice in the middle troposphere and at high latitudes. The study found that the overall climate impacts of hail or graupel at 100km horizontal grid spacing are small, but increase at smaller length scales. Thus while the global climate impact of rimed ice in stratiform clouds may be negligible, there are potentially important and systematic regional effects, such as in orographic precipitation.

In additional microphysics developments, Tao et al. [2019] presented the details of the different microphysics schemes that are used in the Goddard Cumulus Ensemble Model (GCE), the NASA Unified Weather Research Forecast (NU-WRF) and the Multi-scale Modeling Framework (MMF) model. The microphysics schemes are Goddard three class ice (3ICE) and four class ice (4ICE), the Morrison two moments (2M) scheme, and the Colorado State University Regional Atmospheric Modeling System (RAMS) 2M five class ice, and spectral bin microphysics schemes. The performance of these schemes were examined and compared with radar and satellite observations, and an inter-comparison of different microphysics schemes was conducted.

Luo et al. [2018] studied diagnostics of convective transport from the marine boundary layer to the upper troposphere using airborne in situ measurements of chemical species over the tropical western Pacific. Using volatile organic compounds with photochemical lifetimes ranging from shorter than a day to multiple decades, they derived a transit time spectrum and mean transit times for the UT air mass over the convectively dominant tropical western Pacific region. The transit time scale is broadly comparable to that estimated from convective mass flux and has the potential to serve as an effective diagnostic for evaluating the representation of convective transport in global models.

Ocean Modeling and Atmosphere/Ocean Coupling Advances:

Torres et al. [2018] studied partitioning of ocean motions into internal gravity waves and balanced motions, by using a model to understand their signatures on surface ocean fields that could be detected from space. Results reveal a complex picture worldwide of the partition of motions between IGWs and BMs in the different surface fields (surface kinetic energy, sea surface height, sea surface temperature, sea surface salinity, relative vorticity, and divergence fields), depending on the season, the hemisphere, and low and high eddy kinetic energy regions.

An important issue concerning atmospheric ocean coupling and data assimilation concerns errors in atmospheric/ocean fluxes. Strobach et al. [2018] address this issue by comparing surface net heat flux from a state-of-the-art atmospheric reanalysis, the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), to net heat flux from a state-of-the-art ocean state estimate, the Estimating the Circulation and Climate of the Ocean Version 4 (ECCO-v4). The possible impacts of the MERRA-2 and ECCO-v4 air-sea net heat flux difference in a coupled DA system were assessed. When MERRA-2 surface fields are used to force MITgcm, imbalances in the energy and the hydrological cycles of MERRA-2 propagate to the ocean. When MITgcm is forced with MERRA-2 state variables, the errors are shifted to the water cycle, resulting in a global mean sea level increase of 2.7 m. The results have implications for ocean-model forcing recipes and clearly reveal the undesirable consequences of limiting the feedbacks in either of these types of experiments or in coupled DA.

Ocean biology modeling was addressed in Triest et al. [2018], which inferred connectivity distances of the seagrass *Ruppia cirrhosa* along European coastal lagoons using a population genetic imprint and modeled dispersal trajectories using an eddy-resolving numerical ocean model that includes tidal forcing (the MITgcm initialized from a data-constrained global ocean solution provided by the ECCO2 project.) Their findings indicate that strong differentiation or admixtures shaped historical connectivity and that a pre- and post last glacial maximum genetic imprint of *R. cirrhosa* along the European coasts was maintained from their occurrence in primary habitats.

Understanding and Modeling of the Madden-Julian Oscillation was advanced by Ahn et al. [2019], which addressed the issue of the trade-off between cumulus parameterization modifications that improve simulation of the MJO at the expense of the atmospheric mean state. Sensitivity studies with a general circulation model that parameterized mesoscale convective organization showed that such a parameterization helps general circulation models to mitigate the MJO-mean state trade-off. Yang et al. [2019] also studied parameterization of the missing effects of mesoscale convection in GCMs by adding eddy transfer of momentum and temperature by the MCSs. Improvement is explained by a three-way interaction mechanism between the simulated MJO, parameterized upscale impact of MCSs, and background vertical shear. Stan and Straus [2019] studied the MJO as represented in CCSM4 and SP-CCSM4, and found that patterns of low-level atmospheric circulation anomalies and convection associated with the MJO are affected by the method used for the representation of cloud processes. The configuration of the model using super-parameterization for the representation of cloud processes produces MJO-related patterns that agree better with observations than the configuration of the model using a conventional cloud parameterization scheme. The potential changes to the Madden–Julian oscillation (MJO) in response to greenhouse gas–

induced warming during the twenty-first century was studied by Rushley et al. [2019]. Changes in the MJO's amplitude, phase speed, and zonal scale were examined in five models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) that demonstrate superior MJO characteristics. Under warming, the CMIP5 models exhibited a robust increase in the spectral power of planetary-scale, intraseasonal, eastward-propagating (MJO) precipitation anomalies. The MJO's acceleration in a warmer climate resulted from enhanced horizontal moisture advection by the steepening of the mean meridional moisture gradient and the decrease in zonal wavenumber, partially offset by the lengthening of the convective moisture adjustment time scale and the increase in gross dry stability.

Land and Land/Atmosphere Coupling Advances

Modeling of land/atmosphere interactions is a priority of Earth system modeling within CVC, as land surface processes appear to be important to climate prediction on sub-seasonal to seasonal timescales. Land/atmosphere interactions are also important as a main driver of Earth's surface water and energy budgets - they modulate near-surface climate, including clouds and precipitation, and can influence the persistence of extremes such as drought. Santanello et al. [2018] provide an overview of the GEWEX Local Land–Atmosphere Coupling (LoCo) project and working group, formed to examine land/atmosphere interactions at the process level, focusing on understanding and quantifying these processes in nature and evaluating them in models. LoCo has produced an array of land/atmosphere coupling metrics for different applications and scales.

The effects of agriculture on land-atmosphere coupling were investigated by McDermid et al. [2018], by conducting sensitivity experiments using the GISS Model E with modified vegetation characteristics to represent modern crop cover and management, using observed crop-specific leaf area indexes and calendars. The experiments showed that modern intensive agriculture has significant and geographically varying impacts on regional evaporative regimes and background climate conditions. For instance, over the northern Great Plains, modern crop intensity increases the model simulated precipitation and soil moisture, weakening hydrologic coupling by increasing surface water availability and reducing moisture limits on evapotranspiration. The study highlights the need for improved representations of agriculture in global climate models to better account for regional climate impacts and interactions with other anthropogenic forcings.

Bechtold et al. [2019] add a peatland-specific land surface hydrology module ("PEAT-CLSM") to the Catchment Land Surface Model (CLSM) of the NASA Goddard Earth Observing System (GEOS) framework. PEAT-CLSM uses the basic structure of CLSM and the same global input data. A suite of CLSM and PEAT-CLSM simulations for peatland areas between 40°N and 75°N was evaluated against a newly compiled dataset of groundwater table depth and eddy covariance observations of latent and sensible heat fluxes in natural and semi-natural peatlands. PEAT-CLSM simulates a mean groundwater table depth of -0.20 m (snow-free unfrozen period) with moderate temporal fluctuations (standard deviation of 0.10 m), in significantly better agreement with in situ observations.

Evapotranspiration was reduced by 19% and constitutes a significant improvement relative to eddy covariance measurements.

Susskind et al. [2019] compared surface temperature anomalies derived from the Atmospheric Infrared Sounder (AIRS) satellite with the Goddard Institute for Space Studies surface temperature anomaly data set over the period 2003 to 2017. The GISS data set is derived from station data, so the two data sets are produced with completely different methodologies. There is a substantial agreement between the two data sets, providing support to the longer GISS data set and the methodology employed to derive it. This result is relevant to climate modeling due to the importance of surface temperature anomaly data to the evaluation of climate models.

Cryospheric Modeling Advances

Understanding the processes controlling sea level rise (SLR) and accurately projecting SLR over multidecadal time scales is one of the most pressing issues confronting the CVC focus area at this time. Accurate projections depend not only on properly representing the controlling processes within models but properly initializing the model projections. Serrousi et al. [2019] describe an "initial state intercomparison exercise" (initMIP) for the Antarctic ice sheet to compare, evaluate, and improve initialization procedures and estimate their impact on century-scale simulations. InitMIP-Antarctica is part of the CMIP6 Ice Sheet Model Intercomparison Project. For this exercise, 25 simulations were performed by 16 international modeling groups. The exercise found good agreement among model responses to the initial surface mass balance anomaly case but large variations in responses to the basal melting initial anomaly. These variations can be attributed to differences in the extent of ice shelves and their upstream tributaries, the numerical treatment of grounding line, and the initial ocean conditions applied, suggesting that ongoing efforts to better represent ice shelves in continental-scale models should continue.

The rate of growth or retreat of the Greenland and Antarctic ice sheets remains a highly uncertain component of future sea level change. Alexander et al. [2019] examined the simulation of Greenland ice sheet surface mass balance (GrIS SMB) in the NASA (GISS) ModelE2. They compared ModelE2 simulated GrIS SMB for present-day (1996-2005) with SMB simulated by the much higher resolution Modèle Atmosphérique Régionale (MAR) regional climate model at a 25 km resolution. ModelE2 SMB agrees well with MAR SMB on the whole, but there are distinct spatial patterns of differences and large differences in some SMB components. The impact of changes to the ModelE2 surface were tested, including a sub-grid-scale representation of SMB with surface elevation classes. This has a minimal effect on ice sheet-wide SMB, but corrects local biases. Replacing fixed surface albedo with satellite-derived values and an age-dependent scheme has a larger impact. The study also found that lower surface albedo can enhance the effects of elevation classes.

Brunke et al. [2018] evaluate the Regional Arctic System Model version 1, developed to provide high-resolution simulations of the Arctic atmosphere–ocean–sea ice–land system, by comparing retrospective simulations from RASM1 for 1990–2014 with the Community Earth System Model version 1 (CESM1) and the spread across three recent reanalyses. Evaluations of surface and 2 m air temperature, surface radiative and turbulent fluxes, precipitation, and snow depth were performed RASM1 monthly mean surface temperature and radiation biases are shown to be due to biases in the simulated mean diurnal cycle, revealing the need to improve the representation of the diurnal cycle of radiative and turbulent fluxes. However, RASM1 captures the interannual and interdecadal variability in the climate of the Arctic region, which global models like CESM cannot do.

Schlegel et al. [2018] study the effects of uncertainties in model forcing and boundary conditions on ice sheet model simulations. With use of sampling techniques embedded within the Ice Sheet System Model (ISSM) framework, the study examined how uncertainties in snow accumulation, ocean-induced melting, ice viscosity, basal friction, bedrock elevation, and the presence of ice shelves impacted continental-scale 100-year model simulations of Antarctic Ice Sheet (AIS) future sea level contribution. The study found that the AIS sea level contribution is strongly affected by grounding line retreat, which is driven by the magnitude of ice shelf basal melt rates and by variations in bedrock topography. In addition, the study found that over 1.2m of AIS global mean sea level contribution over the next century is achievable, but not likely, as it is tenable only in response to unrealistically large melt rates and continental ice shelf collapse.

Chemistry/Climate Modeling Advances

Integrating atmospheric aerosol and chemistry into NASA's Earth System Models and utilization of the models to address the associated climate-related science questions is one of the priorities of the CVC focus area. Hu et al., [2018] describe the integration of the Harvard GEOS-Chem chemistry and transport model (CTM) with the NASA GEOS ESM for a full-year global simulation of tropospheric ozone chemistry at cubed-sphere c720 ($\sim 12.5 \times 12.5$ km2) resolution. GEOS-Chem is one of the most widely-used CTMs in the world and is continuously updated as understanding of atmospheric chemical processes improves. Its seamless integration with the NASA GEOS ESM allows the immediate inclusion of the most advanced description of atmospheric chemical processes within the GEOS ESM. The integration was facilitated by the extensive use of Earth System Modeling Framework (ESMF) code within the GEOS-Chem and GEOS ESM [Hill et al., 2004].

Yang et al. [2019] examined transport from the Northern Hemisphere (NH) midlatitudes to the Arctic to understand the role in determining the abundance of trace gases and aerosols that are important to Arctic climate via impacts on radiation and chemistry. The Hadley Cell (HC)-related zonal-mean meridional transport rather than the jet-related eddy mixing is the major contributor to the inter-model spread in the transport of land-based tracers into the Arctic. Specifically, in models with a more northern jet, the HC generally extends further north and the tracer source region is mostly covered by surface southward flow associated with the lower branch of the HC, resulting in less efficient transport poleward to the Arctic.

Nicely et al. [2018] examined the stability of the inferred concentration of tropospheric [OH] over the last several decades, despite rising levels of methane that should have led to a decline. The analysis suggests the positive trends in [OH] due to H2O, NOx, and overhead O3, and tropical expansion are large enough to counter almost all of the expected decrease due to rising methane over the period 1980 to 2015, while variations in temperature contribute almost no trend.

Strode et al. [2018] found that Goddard Earth Observing System Model version 5 (GEOS-5) forecasts and analyses show considerable skill in predicting and simulating the CO distribution and the timing of CO enhancements observed during the ATom-1 aircraft mission. They found a dominant contribution from non-biomass-burning sources along the ATom transects except over the tropical Atlantic, where African biomass burning makes a large contribution to the CO concentration. This demonstrates the capability of the GEOS ESM.

Ayarzaguena et al. [2018] examined the question of future Stratospheric Sudden Warming (SSW) changes over the 21st century, using an identical set of metrics applied consistently across 12 different models participating in the Chemistry–Climate Model Initiative. The analysis suggested that no statistically significant change in the frequency of SSWs will occur over the 21st century, irrespective of the metric used for the identification of the event. Changes in other SSW characteristics – such as their duration, deceleration of the polar night jet, and the tropospheric forcing - were also assessed, and the study found no evidence of future changes over the 21st century.

Tweedy et al. [2018] examined the impact of boreal summer ENSO events on tropical lower stratospheric ozone using the Whole Atmosphere Chemistry-Climate model. The interannual variability during boreal summer is highly correlated with summer sea surface temperatures in the eastern and central Pacific Ocean and El Niño–Southern Oscillation (ENSO) events. Larger variability in NT ozone is primarily due to meridional advection, connected to the changes in the onset date and strength of the Asian summer monsoon anticyclone. The Asian summer monsoon anticyclone forms earlier in the season and tends to be stronger during cold (La Niña) events leading to more isentropic transport of ozone from the extratropics into the NT, with the reverse for warm (El Niño) events.

Climate Prediction Advances

Bias correction is a technique to improve short-term climate forecasts. Chang et al. [2019] examine the bias correction problem in current climate models. They focus on the extent to which correcting biases in atmospheric tendencies improves the model's climatology, variability, and forecast skill at subseasonal and seasonal time scales, in the GEOS model. For the uncoupled, atmosphere-only model, they use tendency bias correction (TBC) on a stunted North Pacific jet and a dry bias over the central United States during boreal summer, errors that are common to many current AGCMs. TBC eliminates the jet bias, substantially increases the precipitation over the Great Plains and greatly improves storm-track activity throughout the northern midlatitudes. For a coupled atmosphere-ocean model, the atmospheric TBCs produce substantial improvements in mean climate and variability, reducing the SST warm bias, improving ENSO-related SST variability and teleconnections, and subtropical jets and related submonthly transient wave activity. However, despite these improvements, the improvement in subseasonal and seasonal forecast skill over North America is modest. This is due to the competing influences of predictability loss with time and the time it takes for climate drift to first have a significant impact on forecast skill.

Shin et al. [2019] investigated the dominant modes of the Asian summer monsoon (ASM) rainfall variability, as well as their seasonal predictive skill and predictability using two sets of seasonal hindcasts made with the NCEP Climate Forecast System (CFSv2). CFSv2 is capable of skillfully predicting the dominant ASM modes on the seasonal time scale up to 5 months in advance. Zhang [2018] examined the predictable patterns and intra-ensemble variability of monthly 850-hPa zonal wind over the tropical Indo-Pacific region using 7-month hindcasts for 1983–2009 initialized in May and November. the most predictable patterns are associated with El Niño–Southern Oscillation (ENSO). The second most predictable patterns with May initialization reflect the anomalous evolution of the western North Pacific (WNP) monsoon, characterized by a northward shift of the WNP anomalous anticyclone/cyclone in summer and a southward shift in fall. Seo et al. [2018] used a global land–atmosphere coupled model, the land–atmosphere component of the Global Seasonal Forecast System version 5, to quantify the degree to which soil moisture initialization could potentially enhance boreal summer surface air temperature forecast skill. Forecast skill enhancement appears especially in the areas in which the evaporative fraction—the ratio of surface latent heat flux to net surface incoming radiation—is sensitive to soil moisture amount. These areas lie in the transitional regime between humid and arid climates. Examination of the extreme 2003 European and 2010 Russian heat wave events revealed that the regionally anomalous soil moisture conditions during the events played an important role in maintaining the stationary circulation anomalies, especially those near the surface.

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FY 2019 Annual Performance Indicator	FY 16	FY17	FY18	FY19
ES-19-9: 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-19-11: 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.

Introduction

NASA's Earth Surface and Interior focus area (ESI) continues to advance the understanding of core, mantle, and lithospheric structure and dynamics, and interactions between these processes and Earth's fluid envelopes. Research conducted in the past year has also provided the basic understanding and data products needed to inform the assessment and mitigation of natural hazards, including earthquakes, volcanic eruptions, and landslides. 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): 1. [Plate boundaries], 2. [Tectonics and surface processes], 3. [Solid Earth and sea level], 4. [Magmatic systems], 5. [Deep Earth], 6. [Magnetic field], and 7. [Human impact]. The ESI chapter summarizes highlighted accomplishments of the past year that respond to addressing these seven *CORE* challenges. Referenced ESI publications are also archived on ESDpubs.

Lithospheric Processes

Lithospheric structure and dynamics, and interactions between these processes and the oceans, hydrologic system, and atmosphere are critical to understanding the Earth system. This includes the motion and rotation of tectonic plates, elastic properties of the crust and mantle, and the effects of surface loading resulting from surface water, ground water, other fluids, glaciers, and ice sheets. Studies of slow earthquakes continued to contribute to our understanding of the seismic energy budget. Studies of volcanoes from space saw advancements in arc-scale volcanic activity inventories and new instrumentation developments. Hydrogeodesy continues to emerge as a growing field of study, with important advancements in understanding connections between natural and anthropogenic fluid flux and solid-Earth deformation. The contribution of vertical land motion to rates of relative sea level rise continues to be a major insight provided by ESI research. Many of these studies also represent enabling research for the hazards advancements described in the following section. Below are highlights of ESI Focus Area funded research accomplishments that have matured in FY2019 and represent research that has been funded over the past several ROSES cycles.

Earthquake Processes/Slow-Slip Events
Since the discovery of slow slip events (SSEs) more than two decades ago, it has been suggested that SSEs may trigger seismic events such as earthquakes and long-lived

tremors. Advances in geodetic techniques have enabled the detection and improved the accuracy of SSEs, however, it has been difficult to investigate the physical mechanism linking SSEs to seismic events. The publications described below reveal intriguing new insight into the relationship between SSEs and earthquake processes.

Luo & Liu (2019: *Geochem., Geophys., Geosyst.*) modeled changes in SSE before and after large earthquakes with numerical simulations using a simplified subduction zone fault model that incorporates both the megathrust earthquake and SSE region. The model revealed that the recurrence interval and peak slip rate of SSEs decreased significantly right before the megathrust earthquake. It further showed that repeating SSEs are sensitive to stress perturbations, which can cause SSEs to advance or delay after large earthquakes. Voss et al. (2018: *Science Advances*) analyzed a well-recorded SSE beginning 6 months prior to the magnitude 7.6 earthquake in Costa Rica to explore possible triggering by the SSE. Peak slip rate reached a maximum of 5 mm/day (a few times the background slip rates measured in preceding years), 43 days prior to the earthquake and remained high leading up to the earthquake. The results from both studies suggest that near-term hazard forecasts should incorporate information about the timing of SSEs, particularly as a fault enters the later stage of the earthquake cycle.

Long-lived tremor signals, in contrast with classical earthquakes, are made up of a large number of low-frequency earthquakes that are thought to be due to the activation of small seismic asperities by surrounding slow slip. Due to geodetic detection limitations, these tremor signals are not easy to observe. Rousset et al. (2018: *Science Advances*) used the timing of transient tremor activity, and the dense Parkfield-area GPS network, to detect deep SSEs at 16-km depth on the Parkfield segment with an average moment equivalent to magnitude 4.90 ± 0.08. The discovery and characterization of this deep SSE provides an important constraint for the next generation of Parkfield seismic cycle models.

Panda et al. (2019: *Nature*), used GPS and GRACE data to analyze seasonal variations of continental water storage and its temporal evolution in Southeast Asia to better understand the interaction between seasonally-induced non-tectonic and tectonic deformation along the Himalayan plate boundary. The study suggested that the substantially higher transient displacements above the base of the seismogenic zone indicate the role of changes in aseismic slip rate on the deep megathrust that may be controlled by seasonal hydrological loading. They concluded that non-tectonic seasonal stress perturbations on tectonic deformation ultimately influences the timing of central Himalayan earthquakes.

Magmatic Processes

There is a continued need for higher temporal and spatial resolution, multi sensor observations to understand volcanic processes. One area of future research identified in the *CORE Report* [4. Magmatic systems], states "the use of airborne and spaceborne spectral instruments to provide unique thermal and chemical information on active volcanoes." The publications underlined below address this objective, emphasizing the use of thermal measurements to identify active volcanoes and assess lava propagation and cooling processes.

The thermal infrared (TIR) region of the spectrum has been used to study, monitor, and forecast volcanic activity for decades, yet these data have not always been used systematically at high spatial resolution to study changes in volcano temperature. Reath et al. (2019: *Journal of Volcanology and Geothermal Research*), developed a first-of-a-kind ASTER Volcanic Thermal Output Database (AVTOD) that used manual analysis to identify and collect data for volcanic thermal output with 90 m/pixel spatial resolution for 330 potentially active volcanoes found in Latin America between the years 2000–2017. A total of 88 of these volcanoes were found to have some type of volcanic thermal feature detected by ASTER, including 16 which were detected from space for the first time. This database provides new insights about volcanic activity as well as a data-driven approach to improve key features in future sensors. On a localized scale, Thompson et al. (2019: *IEEE Trans. Geosci. Remote Sens.*) developed a new portable, ground-based imaging system, the miniature multispectral thermal camera (MMT-Cam), to investigate the thermal properties of volcanic processes during lava propagation and cooling at critical temporal (seconds) and thermal (initial rapid cooling) scales. These improved acquisition parameters provide valuable data for both compositional and textural spatiotemporal variability analyses of volcanic surfaces. Furthermore, the MMT-Cam specifications are comparable to current and proposed Earth-orbiting TIR instruments and can be used to evaluate the potential for future TIR data sets.

Hydrogeodesy
Advances of space geodesy over the past decade have enabled transformative research progress in the rapidly evolving field of hydrogeodesy. Space-based observations (e.g. GRACE-FO), advanced geodetic techniques (e.g. GPS, InSAR) and groundwater level records can be combined to identify and understand interactions between hydrologic and solid-Earth processes. Six of the seven science challenges identified in the *CORE Report* either directly address water as a signal source or the need to mitigate the effect of water in the geodetic time-series to advance our understanding of the science. Investigation of these challenges helps bring us closer to understanding how natural and anthropogenic changes in water shapes solid-Earth processes. The hydrogeodesy studies described below investigate how extensive drought and groundwater extraction impacts surface subsidence as well as earthquake processes.

California’s Central Valley is one of the world’s most productive agricultural regions and is highly dependent on groundwater resources. Ojha et al. (2019: *J. Geophys. Res.: Solid Earth*) found that groundwater extraction combined with a prolonged period of drought from 2012-2015, severely impacted the San Joaquin Valley aquifer system and caused permanent loss of groundwater and aquifer storage capacity. As various complementary measurements were analyzed in this study, the consistency in results between GPS and GRACE highlight the advantage of using vertical land motion data to evaluate groundwater loss and thus fill the gaps between GRACE and GRACE-FO missions. To investigate the evolution of ground deformation in response to the 2012-2015 drought and its eventual recovery in the Central Valley, Murray & Lohman et al. (2018: *Science Advances*), constructed and interpreted InSAR time series in the Tulare Basin. They found that despite increased precipitation in early 2017 and an initial decrease, and in some areas reversal, of subsidence rates, within a matter of months, subsidence returned to rates observed during the drought. Taken together, these studies highlight the capability of space-based geodesy to provide insight into the response of groundwater systems to variations in precipitation and water usage, and enable efforts to mitigate impacts from the loss of groundwater resources.

Scientists have tried to understand for decades how different natural forces pressing on Earth's surface might help explain changes in earthquake rates— fluctuations in hydrological loading cycles is one such stress. Wang et al. (2019: *Geophysical Research Letters*) used InSAR data to investigate potential mechanisms responsible for the shallow seismicity in the 2016 Petermann Ranges earthquake in central Australia. They found that the most plausible mechanism driving the observed postseismic surface deformation was a combination of poroelastic rebound and afterslip. The inferred afterslip, overlapping spatially with the coseismic rupture, stressed that the postseismic slip was coupled with the pore fluid flow around the fault zones. Similarly, Luginbuhl et al. (2019: *Pure Appl. Geophys*) applied nowcasting, a new method of statistically classifying seismicity, to induced seismicity due to fluid injection in earthquakes in Oklahoma. The method illustrated that fluid injection induced a rapid build-up of seismicity and a subsequent reduction in seismicity associated with a reduction in fluid injections.

Solid-Earth Contributions to Relative Sea Level Change

The contribution of vertical land motion to rates of relative sea level rise continues to be a major insight provided by ESI research. Improved models of relative sea level rise incorporate geodetic techniques (i.e., InSAR, GPS, and lidar), to characterize both localized and regional natural and anthropogenic coastal subsidence/uplift; and gravity field measurements from GRACE, monitoring sea level change and ice mass balance. The following two publications exemplify how these techniques are used in relative sea level rise and mass variability models.

Based on analysis of gravity field measurements from GRACE, a number of results have provided new insights into seismic cycle processes at subduction zones. Following the magnitude 8.1 Samoa-Tonga earthquake doublet (megathrust + normal faulting) in September 2009, Han et al. (2019: *J. Geophys. Res*) used GRACE and GPS data to detect large-scale gravity increases (0.5 μGal/year, roughly equivalent to a centimeter in equivalent water height change) and ongoing subsidence (8–16 mm/year). Given this intensified subsidence, postseismic rates of relative sea level rise in the surrounding islands increased.
The greatest postseismic subsidence was observed for American Samoa, resulting in a relative sea level rise rate~5 times faster than the global average sea level rise (3.4 mm/yr).

Geodetic investigations of crustal motions have recently highlighted the stabilizing role of solid-Earth uplift on polar ice sheets. One critical aspect, not previously assessed, is the impact of short-wavelength uplift generated by the solid-Earth response to unloading over short time scales close to ice-sheet grounding lines. Larour et al. (2019: *Science*), found that as grounded ice retreats inland, the bedrock under it lifts up elastically. When incorporated into their new global simulation of the Antarctic, this uplift showed a negligible effect during the 21st century. However, around the year 2250 the effect became important; significant stabilization in grounding-line migration occurred when uplift rates started approaching 10 cm/yr for Thwaites Glacier. Although this effect will not stop or reverse ice sheet loss, it could delay the progress of dynamic mass loss of Thwaites Glacier by approximately 20 years.

Natural Hazards Research

New and innovative natural hazards research and analysis is providing insights into understanding risk from earthquakes, volcanic eruptions, and landslides. This includes assessments of processes underlying seminal events, as well as developments in monitoring and forecasting methodologies. Recent studies have also quantified how geodesy can inform our understanding of impacts from Hurricanes, both in terms of total water load and as drivers of land subsidence. 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].

Earthquakes

The determination of earthquake risk for geographic regions has been associated with the development of methods for prediction and forecasting. Bao et al. (2019: *Nature Geoscience*) explored the 2018 magnitude 7.5 Palu earthquake, finding seismological evidence of an early and persistent supershear rupture that propagated steadily at a speed thought to be unstable. By exploiting remote sensing observations (i.e. SAR, optical) of the rupture trace geometry, they found connections between the earthquake's rupture dynamics and fault structure properties, which if mapped in advance, could anticipate the impact of future earthquakes. Furthermore, since supershear ruptures have the potential to generate strong ground shaking carried by Mach wave fronts, the aggravated impact on other natural hazards (e.g. landslides, tsunami) should be considered. Rundle et al. (2019: *Earth and Space Science*) combined nowcasting, a new method developed to determine earthquake risks, with seismic information entropy, to analyze the information contained in earthquake magnitudes for great earthquakes and mega-tsunamis. They found that the earthquake potential score values were similar to the values using only natural time. However, future applications should include other characteristics of earthquake sequences, such as the interevent time intervals or the departure of higher magnitude events from the magnitude-frequency scaling line.

Volcanoes

Owing to practical limitations, especially at remote or heavily vegetated volcanoes, less than half of Earth's 1400 subaerial volcanoes have ground monitoring and few are monitored consistently. Thus, current and future Earth-observing satellite missions, with global and frequent measurements of volcanic activity, are critical. The following two studies highlight the power of space-based imaging in monitoring volcanoes around the globe.

Furtney et al. (2018: *Journal of Volcanology and Geothermal Research*) integrated satellite-detections of ground deformation, SO_2 emissions, and thermal features, of which each contributed unique detections, validating a multi-sensor approach. The study found that most volcanic eruptions in the past few decades were measurable from satellites, and those not detected were associated with low volcano explosivity index eruptions and occurred in the earlier decades of remote sensing (pre-2000) when detection thresholds were high. Dzurisin et al. (2019: *Earth Sci.*) further highlighted recent advancements in remote sensing of volcanoes, specifically summarizing how the arrival of space-based imaging radar has enabled innovative volcano research within the United States. Their findings include: (1) prevalence of volcano deformation in the Aleutian and Cascade arcs; (2) surface-change detection and hazard assessment during eruptions at Aleutian and Hawaiian volcanoes; (3) geodetic imaging of magma storage and transport systems in Hawai'i; and (4) deformation sources and processes at the Yellowstone and Long Valley calderas. Together, with recent and planned launches of highly capable imaging-radar satellites, these findings support an optimistic outlook for near-real time surveillance of volcanoes at a global scale in the coming decade. Based on the wealth of new information about volcanic systems and processes gathered in recent decades, space-based imaging offers an effective volcano monitoring and research tool for the foreseeable future.

Landslides

Documenting the behavior of landslides in response to ongoing climate shifts (e.g. precipitation) and environmental perturbations (e.g. earthquakes) is essential for understanding the mechanisms that control landslide movement as well as for forecasting catastrophic failure. Handwerger et al. (2019: *Scientific Reports*) used InSAR and a simple 1D hydrological model to characterize 8 years of stable sliding of the Mud Creek landslide, California, USA, prior to its rapid acceleration and catastrophic failure on May 20, 2017. Their results suggest a large increase in pore-fluid pressure occurred during a shift from historic drought to record rainfall that triggered a large increase in velocity and drove slip localization, overcoming the stabilizing mechanisms that had previously inhibited landslide acceleration. Thus, in areas posed for climate-induced increases in precipitation extremes, stable landslides could be susceptible to catastrophic failure. As demonstrated by Bouali et al. (2019: *Remote Sensing*), both space (e.g. SAR, optical, and GPS) and airborne (repeat field monitoring and mapping) based measurements are needed as they offer complimentary approaches to determine changes in landslide activity through time.

Hurricanes and vertical land motion

On 26 August 2017, Hurricane Harvey struck the Gulf Coast as a category four cyclone depositing ~95 km^3 of water, making it the wettest cyclone in U.S. history. Using geodetic techniques, ESI scientists highlighted the impact from Hurricane Harvey on total water load and land subsidence. Milliner et al. (2018: *Science Advances*) demonstrated the ability of GPS networks to remotely track the spatial extent and daily evolution of terrestrial water storage following Hurricane Harvey. They found a clear migration of subsidence (up to 21 mm) and horizontal motion (up to 4 mm) across the Gulf Coast, followed by gradual uplift over a 5-week period. This study has important implications for improving operational flood forecasts and understanding the response of drainage systems to large influxes of water. Miller & Shirzaei (2019: *Remote Sensing of Environment*) mapped the flooded area using the radar backscattering difference between Sentinel-1A/B satellite acquisitions spanning the Hurricane Harvey event. Although flooding during Hurricane Harvey resulted primarily from heavy rainfall, this study found the correlation to localized land subsidence to be robust, as subsidence maps of the area showed 85% of the flooded area had subsidence rates of >5 mm/yr, larger than the rate of mean global sea level rise at ~3 mm/yr. This study highlights the importance of incorporating InSAR measurements of land subsidence in future flood resilience strategies.

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. NASA ESI studies also continued to make unique contributions to magnetic field data products representing sources from the core outward. While addressing advances in CORE challenges [5. Deep-Earth, 6. Magnetic field] the studies described below highlight connections to other CORE challenges [1. Plate boundaries, 2. Tectonics and surface processes, 3. Solid Earth and sea level].

Earth Rotation

Astrometric and geodetic measurements show that the mean position of Earth's spin axis drifted toward Labrador, Canada at an average speed of 10.5 ± 0.9 cm/yr during the 20th century. Understanding this secular polar motion (SPM) is important in global climate modeling, as it provides a link to ice mass balance and sea-level rise. Although glacial isostatic adjustment (GIA) models reasonably explain the direction of SPM, the associated prediction of the amplitude is lacking. Based on the Bayesian GIA analysis carried out by Adhikari et al. (2018: *Earth Planet. Sci. Lett.*), GIA only explained 33±18 % of the observed SPM amplitude. Taking the summed signals (i.e. Earth's surface mass transport derived from recent advancements in modeling the global 20th century cryospheric, hydrologic, oceanic, and seismogenic mass exchange) into account could not fully reconcile the observed SPM amplitude. Thus, an additional excitation source, changes in Earth's inertia tensor caused by mantle convection (MC), was investigated using sophisticated models. By accounting for the contribution from MC, the gap between observation and prediction was significantly reduced. Accordingly, this study concluded that long-term mass movement due to mantle convection is a key mechanism for driving 20th century SPM.

Length of day (LOD) variations at a ~6-year period have been shown to be strongly coherent with occurrence times of the sudden changes of the magnetic field. These variations are thought to be due to core-mantle coupling, which if true, would imply that core flow associated with the ~6-year signal may also deform the mantle, causing a similar signal in the deformation of the Earth's surface. Watkins et al. (2018: *Nature Scientific Reports*), put this idea to test by investigating if the ~6-year LOD signal was due to angular momentum exchange between the solid Earth and outer core. They analyzed the spectrum of 523 stacked GPS radial time series, and found a global ~6-year deformation signal. Further, in some cases, the inverted deformation signal for the outer core's flow and equivalent angular momentum changes, had good agreement with the LOD signal. Although the study results support the idea of subdecadal core-mantle coupling, they are not robust, and further methodological improvements and implementation are needed. This study highlights the potential use of surface deformation data in Earth rotation studies.

Earthquakes cause gravity changes by deforming the Earth and changing ambient densities of the crust and mantle. GRACE satellites have detected regional-scale coseismic and postseismic gravity changes after recent great (Mw>8.0) earthquakes and are based primarily on the analysis of monthly mean solutions of the Earth's gravity field. At shorter time scales, earthquakes also yield transient global-scale gravity changes by exciting free oscillations of the Earth which perturb the orbital trajectory of satellites. Ghobadi-Far et al. (2019: *J. Geophys. Res.*), used normal mode formalism to synthesize the global gravitational changes after the 2004 Sumatra earthquake and further simulated free oscillation signals manifested in the GRACE K-band ranging (KBR) measurements. A few severe normal modes were found to generate range-rate perturbations as large as 0.2 μm/s, which is comparable to actual errors of GRACE KBR. Furthermore, wavelet time-frequency analysis of the GRACE KBR residual data revealed a significant transient signal after the 2004 Sumatra earthquake. This transient signal could potentially be associated with the largest excitation due to the "football" mode of the Earth's free oscillation. However, such signals may be obscured by low frequency noise of the GRACE accelerometers. As demonstrated in this study, improved space-borne gravitational instrumentation may open new opportunities to study Earth's interior and earthquakes independently from global seismological analysis.

Magnetic Field

Temporal and spatial separation of magnetic fields have increasingly improved, although much remains to be accomplished. For example, the ESA three-satellite constellation Swarm has allowed for improved separation of external and internal magnetic sources via its gradient field configuration. In order to exploit these measurements, a modeling approach called comprehensive inversion (CI) has been developed, leading to a well-known series of Comprehensive Models (CM) as well as deriving a consistent set of Swarm Level-2 (L2) magnetic data products. Sabaka et al. (2018: *Earth, Planets and Space*), has developed the latest CI model, denoted as "CIY4," which serves as the source of the fourth version of the L2 magnetic field products, including the new product describing the magnetic signal of the M2 oceanic tide. The resolution achieved with Swarm suggests that other major tidal constituents could conceivably be detected.

Time-variable Gravity Field
Satellite laser ranging (SLR) observations are routinely applied toward the estimation of dynamic oblateness, C20, which is the largest globally integrated component of Earth's time-variable gravity (TVG) field. As such its accurate recovery is of great importance for recovering regional mass variability and understanding changes in the Earth climate system. Loomis et al. (2019: *Geophys. Res. Lett.*), developed a systematic approach in the development of a new C20 solution, which quantified the effect of the data reduction arc length, SLR tracking data weights, GRACE-derived forward models, and expansion of the estimated gravity field. This improved SLR product modified the mass trend in the Antarctic Ice Sheet by -15.4 Gt/yr (>10% of the estimated -127 Gt/yr total), the Greenland Ice Sheet by -3.5 Gt/yr (>1% of -286 Gt/yr), and mass driven sea level rise by +0.08 mm/yr (~2% of the 3 mm/yr global mean sea level change rate). Further, these results improved the agreement with independent data sets as well as with independent length-of-day measurements. This study recommended that this new C20 product be applied to GRACE data products for enhanced accuracy and scientific interpretation.

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. Connected to this is enabling research for SAR, as well as for complementary techniques built on GPS geodetic data.

NASA-ISRO Synthetic Aperture Radar (NISAR) Mission
NISAR (https://nisar.jpl.nasa.gov/) has been in Phase C since August 2016. The project conducted a successful Project Critical Design Review (CDR) in October 2018. Nearly all of the radar flight electronics have been completed. In May 2019, the project entered the initial integration and test phase. Structural hardware to mount the ISRO S-band electronics has been sent to India. Other hardware is flowing back and forth between NASA and ISRO.

Prior to CDR, the solid-Earth subgroup had pressed the project for a re-evaluation of the overall left-looking/right-looking strategy for the observing both poles. SAR systems must point their antenna beam in a direction squinted away from the velocity vector, ideally perpendicular to the flight track. Generally, the ESI community optimizes their science by looking to only one side of the spacecraft, giving continuous time series. However, to observe both poles, the nominal plan looks to the north for 25 cycles out of the year and to the south 5 cycles per year. The solid-Earth team has advocated for partnerships with other agencies to cover the north polar cap so that NISAR can look continuously to the south. The Science Team reached a consensus to follow this recommendation, and it was formally adopted for the mission around the CDR time frame. As a consequence of this change, the mission launch date moved from December 2021 to January 2022.

The science team worked with the project science and mission team to develop a comprehensive “Science Users’ Handbook” that was made available prior to CDR 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. In FY19 the document has been revised to correct errata and update some of the mission characteristics, most notably the decision to operate the mission looking only toward the south.

The solid-Earth team led the way in developing a joint science plan with ISRO, and in the past year, they have continued to add specificity to the plan. 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 was conducted in 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. The November 2018 workshop comprised an InSAR tutorial session followed by sessions on exemplary joint research topics in the earthquake cycle (Himalayan front and elsewhere), volcano monitoring (e.g., Andaman, Indonesia and elsewhere), and hydrogeology (aquifers). There was a final session on NASA science requirements in the solid-Earth area, how they are codified, documented, and validated, and how scientists in the US and India can work together with a common set of tools for validation and doing science. The workshop was well attended, with strong interest in follow-up training and tutorials.

The applications subgroup held two solid-Earth relevant workshops in the areas of volcano hazards and landslides. The outcomes from these workshops are recommendations for product types from the project, useful latencies of data for applications and response purposes, and ways in which stakeholders can interact with the project both during development and operations. Reports are being generated and will be published on the NISAR web site.

A new activity was initiated in the last year to fly the ISRO airborne L/S-band SAR in the US on a NASA aircraft as a joint science activity. This system will mostly focus on ecosystems science, however, there are a number of measurements that will be relevant to solid-Earth investigators, including soil moisture and permafrost. As the team discussed the possibilities and scoped out the experiment plan, solid-Earth team members were active participants in the discussion. The plan is to fly the system over southeast United States and over permafrost, glaciers, and sea ice in and around Alaska in the near future.

The solid-Earth team continued to refine their efforts to establish their Algorithm Theoretical Basis Documents and validation processing as an integrated tool using Jupyter notebooks. Franz Meyer has structured a class around these notebooks and has a cloud interface allowing complete portability; the solid-Earth team has adopted his approach as a way forward.

The Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) Facility
The UAVSAR L-band radar continued to conduct semi-annual observations for the Central San Andreas Fault monitoring study as well as monitoring slow moving landslides in Slumgullion, CO, and Eel River, CA, during the snow melt and rainy seasons respectively.

UAVSAR executed a Hurricane Florence rapid response deployment with the L-band radar to generate prototype inundation extent maps of North and South Carolina with less than 6 hours turnaround time in support of US Army Corps of Engineers, FEMA, USGS, USFS, and University of South Carolina.

Discussions are underway to fly over the area impacted by the M7.1 Ridgecrest, CA Earthquake Sequence. This campaign would offer the opportunity to capture post-seismic deformation signals as well as a base map of the region to facilitate assessment of future activity along this and associated fault systems.

Geodetic Imaging Enabling Research
InSAR and GPS data availability and processing methods are critical to many avenues of ESI science, while also providing high-resolution maps and timeseries of surface deformation applicable to many scientific and applied studies.

Atmospheric noise is a particularly prevalent and challenging component of space-based InSAR observations that must be accounted for to accurately derive underlying surface displacements in the data. Liang et al. (2019: *IEEE Trans.*) addressed the effects of the ionosphere on InSAR time series in a study using C-band Sentinel-1 TOPS data, to improve capabilities for measuring large-scale tectonic motions. Using the range split-spectrum method, so called because the range radar spectrum is split into two subbands, each with a different center frequency, they found that ionospheric effects are very strong for data acquired at low latitudes on ascending satellite tracks. For other cases, ionospheric effects are not strong or even negligible. The application of the range split-spectrum method largely removes ionospheric effects, and thus improves the InSAR time series analysis results.

Blewitt et al. (2018: *Eos*) published a perspective in EOS about “harnessing the GPS data explosion.” The continued development of open access GPS data and products is enabling a broad range of ESI research across nearly all of the *CORE* topics. The publication profiles the Nevada Geodetic Laboratory’s efforts to collate and process data from more than 17,000 GPS stations and provide daily plots of position coordinates, regular updates of station velocities, and associated metadata. The open provision of these products is a resource for the entire Earth science community.

Space Geodesy Program

NASA's Space Geodesy Program (SGP) (http://space-geodesy.nasa.gov/) supports the production of foundational geodetic data that enable positioning, navigation, and timing applications and many of the scientific discoveries and accomplishments highlighted in the other sections of this report. 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 (Merkowitz et al., 2018: *J. Geod.*).

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 (Niell et. al., 2018: *Radio Science*). All three NASA stations and three international partner VGOS stations participated in the VLBI CONT17 continuous campaign that demonstrated the VGOS network to have comparable uncertainties for Universal Time (UT1) as the legacy network. This significant milestone demonstrates the viability of VGOS replacing the legacy network once the network has better geographical distribution. VGOS session data is now being made publicly available on the Crustal Dynamics Data Information System (CDDIS).

The University of Texas completed the facility improvements at the McDonald Geodetic Observatory (MGO) that will support new NASA VGOS and SLR stations. The integration of the MGO VGOS station is underway and scheduled for completion by the end of the Summer 2019. The SGP successfully completed the Space Geodesy Satellite Laser Ranging (SGSLR) Critical Design Review (CDR) for SLR stations at MGO and in Ny-Ålesund, Svalbard (in partnership with Norway), and a number of long-lead procurements for these stations are underway. Construction of the SGSLR integration and test facility building and dome at the GGAO was completed and installation of the available MGO SGSLR hardware has begun.

SGP Data and Analysis
It was another record year in advancing the NASA Space Geodesy Network operations and utilization of attendant data products. The NASA SLR network 2018 annual total data yield increased by 7% over 2017 with 77,862 satellite pass segments (728,188 normal points) tracked. The SLR network currently actively tracks 113 targets, which includes 71 GNSS satellites. The next generation VGOS network had 190,379 scheduled observations in 2018; the legacy VLBI network had 932,283. NASA's global space geodesy data archive and distribution system, CDDIS, experienced another year of record growth and broke last year's data distribution figures by 30% with 2 billion file downloads from 245,000 unique users in 2018. SGP supported researchers contributed to eight journal articles in a special issue of the Journal of Geodesy on Satellite Laser

Ranging, including: Noll et al. (2018: *J. Geod.*), McGarry et al. (2018: *J. Geod.*), and Pearlman et al. (2018: *J. Geod.*).

SGP-supported VLBI observational program and data analysis resulted in the new catalogue of positions of Active Galactic Nuclei for the Third Realization of the International Celestial Reference Frame (ICRF3). ICRF3, the internationally recognized standard for the coordinates of all celestial objects, was put into effect by the International Astronomical Union on January 1, 2019. ICRF3 has 3.5 times better median precision than ICRF2 and contains 33% more sources that will help to improve the accuracy of the Earth Orientation Parameters used for spacecraft navigation and geophysical studies.

Several studies were also completed that improve the precision and accuracy of the space geodetic data products. First, a systematic analysis of LAGEOS-1 & 2 data (1993-2018) was completed that identified and addressed persistent long-term biases at the legacy SLR stations. Incorporating these bias estimates in the processing for the determination of the SLR contribution to the International Terrestrial Reference Frame (ITRF) reduces the discrepancy in scale between SLR and VLBI by about 1 part per billion (>10%). For the next ITRF (2020), the scale produced by VLBI and SLR will be in better agreement than the current and previous realizations. Second, the solar system rotation about the galactic center was observed using VLBI and found to have an effect on the geodetic analysis where the terrestrial and celestial reference frames are estimated. The rotation of the solar system around the galactic center causes an apparent dipolar pattern in the temporal rate of change in the position of VLBI sources (Active Galactic Nuclei) with an amplitude of 5-6 microarcseconds per year (MacMillan et. al., 2019: *A&A*). Finally, a Long Baseline Calibrator Survey of southern hemisphere VLBI radio sources was published by Petrov et al. (2019: *MNRAS*) that eliminated the hemisphere disparity in the density of brighter radio sources with positions determined at milliarcsecond accuracy.

Global GNSS Network

The upgrade of NASA's Global GNSS Network with multi-GNSS receivers was completed early in 2018, allowing for the successful support of GPS Block III measurements this past year.

Deployment of GNSS instrumentation at the VLBI site at the MGO core site was completed. This deployment included installation of modern, multi-GNSS receivers. Co-location of GNSS instrumentation with VLBI and SLR instrumentation is central to the purpose of core sites as "anchors" for International Terrestrial Reference Frame.

JPL Geodetic Analysis Center

Utilizing the increased availability of multi-GNSS measurements from ground stations, including NASA's GGN, JPL has developed a prototype operations system producing advanced precision orbit determination (POD) from GLONASS, BeiDou, and Galileo international positioning systems, in addition to GPS. Following a period of evaluation and validation, these POD products are expected to be made available to NASA and other research users in fiscal year 2020. In addition, JPL is investigating how access to data and

POD products from these satellite constellations can be used to improve precise point positioning and other scientific applications.

JPL has also made progress in transitioning to a multi-technique Geodetic Analysis Center. The capability to analyze Satellite Laser Ranging data is mature to the point it is being utilized in an ongoing Space Geodesy Architecture Trade Study. The capability to analyze data from Doppler Orbitography by Radiopositioning Integrated by Satellite (DORIS) is being developed through a collaboration with IGN, France. GipsyX analysis of DORIS data during testing shows results consistent with results from legacy GIPSY-OASIS software. Development of the VLBI analysis capability is progressing and is expected to be an important tool for research in the following years.

Terrestrial Reference Frame Combination

The Terrestrial Reference Frame is the foundation for positioning and timing for navigation and proper interpretation of scientific measurements. The standard for the most demanding scientific applications is the International Terrestrial Reference Frame (ITRF). Preparations for NASA/JPL support of the next ITRF solution, planned for 2020, are nearing completion. As part of the International Earth Rotation and Reference System Service (IERS) effort to determine an update to the ITRF, "ITRF2020", NASA/JPL is planning on producing three solutions for evaluation by the IERS:

1. A standard solution to be considered as a candidate to be selected as the ITRF2020 solution. In this, NASA/JPL will utilize modernized software to find the optimal combination of Network solutions for each of the major Space Geodesy Techniques (DORIS, GNSS, SLR, and VLBI) and results from local surveys from co-located sites;
2. A TRF solution, based on a combination of network solutions, that also results in a determination of Earth Orientation Parameters and the Celestial Reference Frame;
3. A TRF solution that is based on the combination of observations from the major space geodesy techniques. This solution could lead to a potentially groundbreaking methodology for improving the TRF and, more generally, to significant improvements in positioning and timing of scientific measurements.

All the NASA/JPL TRF solutions have benefit of being easily updated using new measurements, prolonging the time between data reprocessing and selection of new ITRF solutions.

SGP International and Interagency Cooperation

SGP continued to work collaboratively with its international partners. Over the past year, SGP formally renewed its cooperation with Colombia, Kenya, South Africa, Nigeria, and Peru. SGP also renewed its cooperation with the United States Naval Observatory (USNO) for continued VLBI support as part of the National Earth Orientation Service.

After two years as Chair of the Global Geodetic Observing System (GGOS), Richard Gross of JPL has been elected Vice President of GGOS' parent organization, the International Association of Geodesy (IAG). While GGOS Chair, Richard established

GGOS Affiliates to broaden the participation of national and regional geodetic organizations in GGOS, established the position of Manager of External Relations to improve GGOS engagement with external organizations like the Group on Earth Observations and the Committee on Earth Observation Satellites, established a Committee on Essential Geodetic Variables to provide a framework for assigning requirements to geodetic data and products, and established a Working Group on Digital Object Identifiers for Geodetic Data Sets to allow recognition to be given to the providers of geodetic data and products. As IAG Vice President, Richard will continue to advocate for the importance of geodesy to science and society.

SGP continues to be a key participant in the United Nations Global Geospatial Information Management's Subcommittee on Geodesy as the Subcommittee continues to explore options for establishing an international organization to help maintain and enhance the reference frame. Members of SGP are actively advocating for the importance of the reference frame by participating in the Subcommittee's Working Groups on Outreach and Communications; Infrastructure; Governance; and on Education, Training, and Capacity Building. A questionnaire on reference frame competency has been developed and sent to Member States to assess their competency requirements and educational needs in geodesy. The results of the survey will be used to establish a priority list of short- and long-term training needs, their objectives, and the resources required to achieve them.

SGP Contributions to Broad Science Mission Directorate Objectives
SGP started SLR tracking of Gravity Recovery and Climate Experiment Follow-On (Grace-FO) and Ice, Cloud and land Elevation Satellite-2 (ICESat-2), both NASA Earth science missions launched in 2018, and continued SLR tracking of radar altimeter satellites that synoptically monitor the changes in the ocean surface topography (i.e. Jason-2, & Jason-3).

A search for gamma-ray sources via VLBI observations has led to the association of 56% of the Fermi catalogue with VLBI source counterparts. This association improves the source position accuracy up to a factor of 100,000. The improve accuracy makes possible associations with optical and infrared counterparts which enables distance estimates and true multi-wavelength astronomy of Fermi sources.

SGP-developed broadband VLBI technology for its VGOS stations was successfully used by the Event Horizon Telescope (EHT) project, which recently unveiled the first direct image of a black hole. The EHT operates at 230 GHz and VGOS at 10 GHz, but the signal chain backends (i.e., RF distributors, down-converters, digitizers, recorders) are the same. The broadband cluster correlator and post-processing software are supported by both NASA and the National Science Foundation as leveraged efforts between these projects at the Massachusetts Institute of Technology.

Strategic Development and Community Engagement

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

As part of the ongoing National Academy of Sciences study *Evolving the Geodetic Infrastructure to Meet New Scientific Needs* (https://www8.nationalacademies.org/pa/projectview.aspx?key=51264), a two-day workshop was held in Irvine, CA, to discuss key connections between geodesy and priority Earth science questions as identified in the Decadal Survey, and explore how to improve the geodetic infrastructure to meet new science needs. The workshop included participants from multiple Earth science communities and was framed around working sessions on geodetic needs for weather/atmospheric science, water, ecosystems, sea level, and solid-Earth science. Each breakout paired geodesists with discipline experts from these other areas and asked them to identify and quantify geodetic needs for these broad science areas. This study is co-funded by ESI and the Physical Oceanography and Cryospheric Sciences programs.

ESI also played a leading role in community workshops associated with the Decadal Survey Designated Observable studies for Surface Deformation and Change (SDC) and Surface Biology and Geology (SBG). These included the SDC SAR Technology Workshop on May 20-22, 2019, in Pasadena, California; and the SBG Community Workshop on June 12-14, 2019, in Washington, DC.

ESI announced its first annual NASA Solid-Earth Team Meeting to offer opportunities for face-to-face interactions among the broader ESI community, sharing of ESI research highlights, information about upcoming missions, solicitations, and research opportunities, as well as training sessions and tutorials on key capabilities for the ESI community. The inaugural meeting will be held on November 4-6, 2019, at the Scripps Institution of Oceanography in La Jolla, California.

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FY 2019 Annual Performance Indicator	FY 16	FY17	FY18	FY19
ES-19-11: 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