

EARTH SCIENCE DIVISION

TABLE OF CONTENTS

| | | |
|--|------|-----|
| Annual Performance Goal 1.1.8 | Page | 2 |
| 1.1.8.1 Atmospheric Composition | | 2 |
| 1.1.8.2 Carbon Cycle & Ecosystems | | 14 |
| 1.1.8.3 Climate Variability & Change | | 23 |
| 1.1.8.4 Earth Surface & Interior | | 34 |
| 1.1.8.5 Water & Energy Cycle | | 50 |
| 1.1.8.6 Weather & Atmospheric Dynamics | | 63 |
| Annual Performance Goal 1.1.9 | Page | 76 |
| 1.1.9.1 Atmospheric Composition | | 76 |
| 1.1.9.2 Carbon Cycle & Ecosystems | | 90 |
| 1.1.9.3 Climate Variability & Change | | 94 |
| 1.1.9.4 Earth Surface & Interior | | 105 |
| 1.1.9.5 Water & Energy Cycle | | 108 |
| 1.1.9.6 Weather & Atmospheric Dynamics | | 110 |
| References | Page | 123 |

Annual Performance Goal 1.1.8: NASA shall demonstrate progress in characterizing the behavior of the Earth system, including its various components and the naturally-occurring and human-induced forcings that act upon it.

Section 1.1.8.1 Atmospheric Composition Focus Area

The Atmospheric Composition Focus Area (ACFA; <https://science.nasa.gov/earth-science/programs/research-analysis/atmospheric-composition>) provides quantitative global observations from space, augmented by suborbital and ground-based measurements of atmospheric aerosols and greenhouse and reactive gases. These enable the national and international scientific community to improve our understanding of their impacts on climate, air quality and biogeochemistry. In tandem with the observations from ACFA missions and projects, ACFA-sponsored research utilizes and coordinates advances in observations, data assimilation, and modeling to better understand the Earth as a system. Responding to both of the Earth Science Division (ESD)-relevant annual performance indicators, ACFA helped to gain insights into changes in the Earth's radiation balance, our prognostic capability for the recovery of stratospheric ozone, 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, air quality and biogeochemistry.

To demonstrate progress in characterizing the behavior of the Earth system, including its various components and the naturally-occurring and human-induced forcings that act upon it, ACFA sponsored research in FY2021 that aims to

- (a) more fully characterize space-borne measurements of aerosols and clouds in terms of the processes that impact the Earth's radiative flux, in particular the coupling between clouds and aerosols,
- (b) bridge the gap between the high temporal and spatial variability of air quality monitoring with a combination of new space-borne measurements well as expansion of ground-based networks,
- (c) understand the emissions of CO₂, methane (CH₄) nitrous oxide (N₂O) and other gases that persist in the atmosphere over time scales of a decade to centuries with studies involving data from the NASA OCO-2 and OCO-3 missions
- (d) use NASA's portfolio of space-based instruments, in particular OMI and MLS on Aura, together with key ground-based networks like AGAGE and SHADOZ for characterizing the evolution of the multi-decadal ozone recovery process and ongoing changes in radiative forcing and provide the means to monitor compliance with the Montreal Protocol and its amendments.

Each of these topic areas of ACFA-sponsored research employ programmatic and Earth Venture (EV)-class suborbital missions and ground-based networks to reveal details of

atmospheric processes ranging from trace gas emissions to aerosol and cloud formations with higher accuracy and resolution than usually possible from space.

Despite restrictions and delays due to COVID, three ACFA-supported field campaigns employing both airborne and ground-based assets took place during FY2021. Likewise, most of the surface-based observations supported by the focus area have continued to provide regular measurements of a wide range of atmospheric trace constituents.

The following summarizes the three field campaigns' activities:

1. Test flights with the NASA WB-57 were conducted out of Houston in August in preparation for the NASA portion of Asian Summer Monsoon Chemical & CLimate Impact Project (ACCLIP) deployment to Osan AFB in Korea in July and August 2022. A primary goal of ACCLIP is to characterize outflow from the Asian monsoon, and the test flights allowed some focused science to observe Asian outflow that had made its way to the US.
2. The Dynamics and Chemistry of the Summer Stratosphere (DCOTSS) EVS-2 investigation conducted both test and initial science flights on the NASA ER-2 in August out of Salina, Kansas. From this location, the campaign was able to observe the integrated effects of deep overshooting convective processes and the North American Monsoon Anticyclone (NAMA) under late summer conditions. Because DCOTSS and ACCLIP payloads had many similar observations, one flight of each campaign was dedicated to direct inter-comparisons, and these turned out to be quite successful. The early and mid-summer campaigns of DCOTSS will be held in 2022.
3. The Tracking Aerosol Convection Experiment-Air Quality (TRACER-AQ) campaign took place in September in Houston, TX, making measurements of air quality-relevant constituents at high spatial and temporal resolution with a focus on developing capabilities for using geostationary air-quality observations from the upcoming TEMPO mission. For TRACER-AQ, NASA equipped the Johnson Space Center GV aircraft with an air quality-mapping payload including the TEMPO airborne simulator, the Langley HSRL2 and DIAL ozone lidars. NASA also supported two ground-based tropospheric ozone lidars from TOLNET, several Pandora spectrometers, MPLNet, and AERONET instruments, ozonesondes, a mobile laboratory, as well as air quality and weather forecasting support.

Finally, ACFA researchers this past year have made important contributions to understanding the impacts of smoke from wildfires, both on air quality near the surface as well as in the free troposphere and upper atmosphere above it where can impact Earth's radiation balance.

A. Aerosols, clouds and radiative forcing

The ACFA Radiation Sciences Program (RSP) and its associated space-borne missions and sub-orbital projects, as well as the Atmospheric Composition Modeling and Analysis Program (ACMAP), support a broad range research on aerosols, clouds and the Earth's radiative flux. These span ongoing development of aerosol and cloud retrievals and

products, aerosols and cloud radiative effects, and smoke layers and the properties of particles produced by wildfires. Summarized in this section are 13 papers from the more than 60 published in the last year in this topic area.

Aerosol retrievals

The Dark Target (DT) aerosol algorithm was developed to exploit the information content available from the observations of Moderate-Resolution Imaging Spectroradiometer (MODIS) in order to better characterize the global aerosol system. As discussed in [Remer et al. \(2020\)](#), DT was developed over nearly a decade of research that played a significant role in expanding our understanding of aerosol properties. Observations and retrievals from the growing Aerosol Robotic Network (AERONET) of sun-sky radiometers contributed significantly to that understanding, providing validation of satellite-retrieved products after launch. The Dark Target team continues to adapt and apply its well-vetted algorithms to new sensors, both polar-orbiting and geosynchronous, to produce an uninterrupted aerosol climate data record that began in the early 2000s and will continue indefinitely into the future.

[Lee et al. \(2021\)](#) have developed an optical algorithm to retrieve aerosol layer height and single scattering albedo from VIIRS and the OMPS-Nadir Mapper that provides height information over much broader areas than more dedicated space-borne lidars and multi-angle instruments, complementing existing data sets. As part of the upcoming VIIRS Deep Blue aerosol products, the new data sets can be used for various aerosol applications from radiative forcing studies to initialization/evaluation of aerosol transport models.

Spectral absorption is one of the key aerosol properties related to chemical speciation required by the climate modeling and air quality communities. [Lyapustin, et al. \(2021\)](#) introduced a new algorithm for joint retrieval of the aerosol optical depth and spectral absorption from EPIC observations in the UV-Vis spectral range. An initial evaluation of single scattering albedo (SSA) at 443 nm over North America and the greater Sahara regions during 2018 shows a general agreement with AERONET data within the uncertainty of AERONET SSA.

[Yorks, et al. \(2021\)](#) presented the first published results of machine learning (ML) techniques for detecting aerosols and clouds using backscatter lidar data. These ML techniques, when applied to Cloud-Aerosol Transport System (CATS) data (a) increased the 1064 nm SNR by 75%, (b) increased the number of layers detected (any resolution) by 30%, and (c) enabled detection of 40% more atmospheric features during daytime operations at a horizontal resolution of 5 km compared to the 60-km horizontal resolution often required for daytime CATS operational data products. A Convolutional Neural Network (CNN) trained using CATS standard data products also demonstrated the potential for improved cloud-aerosol discrimination compared to the operational CATS algorithms for cloud edges and complex near-surface scenes during daytime. The machine learning tools described not only can improve the accuracy and utility of lidar data products for climate research, but can also reduce the noise in daytime lidar signals

to facilitate the development of smaller, low-cost lidar systems in the future, and enable real-time accessibility of lidar data products from future lidar systems for monitoring and forecasting of hazardous events.

Properties of clouds and cloud structure

Reliable, long-term observations of cloud thermodynamic phase are critical for studies of the Earth's radiation budget. [Lewis et al. \(2020\)](#) have described the cloud thermodynamic phase variable that is now available in the MPLNET Version 3 cloud product. This now provides MPLNET, NASA's network of Micro Pulse Lidars, the capability to provide a full range of continuous observations of cloud properties, including thermodynamic phase, across all climate regions using a standardized instrument and retrieval process.

[Hong and Di Giralomo \(2020\)](#) examined the climatology of cloud phase over Southeast Asia (SEA) using combined CloudSat–CALIPSO (CC) data. They found liquid-only clouds tend to occur in the relatively cold, dry, and stable lower troposphere. In contrast, clouds with ice appear more frequently in relatively warm, humid, and unstable conditions, and their seasonal distributions move with the Asian monsoon and the Intertropical Convergence Zone (ITCZ). Liquid clouds are found to be highly inhomogeneous based on the heterogeneity index (H_{σ}) from MODIS, while ice-only and mixed-only clouds are often very smooth.

For passive satellite imagers, current retrievals of cloud optical thickness and effective particle size fail for convective clouds with three-dimensional (3D) morphology. Indeed, being based on one-dimensional radiative transfer (RT) theory, they work well only for horizontally homogeneous clouds. A promising approach for treating clouds as fully 3D objects is cloud tomography, which has been demonstrated for airborne observations. However, more efficient forward 3D RT solvers are required for cloud tomography from space. [Forster et al. \(2021\)](#) presented an approach to retrieving cloud optical thickness and effective particle size for convective clouds based on the concept of “veiled cores” (VCs). The assumption is that sunlight scattered into and out of these deep regions does not contribute significant information about the inner structure of the cloud to spatially detailed imagery. Investigation of the VC location in imagery from the Multi-angle Imaging SpectroRadiometer (MISR) and MODIS showed that the VC is located at an optical distance of ~ 5 , starting from the cloud boundary along the line of sight. This approach will not only lead to a reduction in the number of unknowns for the tomographic reconstruction but also significantly increase the speed and efficiency of the 3D RT solver at the heart of the algorithm by applying, say, the photon diffusion approximation inside the VC.

Aerosols and cloud radiative effects

[Loeb et al. \(2021\)](#) described a new method for determining clear-sky shortwave aerosol direct radiative effects (ADRE) from the Clouds and the Earth's Radiant Energy System (CERES) instruments on board Terra and Aqua to examine changes in ADRE since 2002

alongside changes in aerosol optical depth (AOD) from MODIS. At global scales, neither ADRE nor AOD show a significant trend. Over the Northern Hemisphere (NH), ADRE increases by $0.18 \pm 0.17 \text{ Wm}^{-2}$ per decade (less reflection to space) but shows no significant change over the southern hemisphere. The increase in the NH is primarily due to emission reductions in China, the United States, and Europe. The study also shows the COVID-19 shutdown had no noticeable impact on either global ADRE or AOD, but there is a substantial impact over northeastern China in March 2020. In contrast, February 2020 anomalies in ADRE and AOD are within natural variability even though the impact of the shutdown on industry was more pronounced in February than March. The reason is because February 2020 was exceptionally hot and humid over China, which compensated for reduced emissions. After accounting for meteorology and normalizing by incident solar flux, February ADRE anomalies increase substantially, exceeding the climatological mean ADRE by 23%.

Human activities releasing greenhouse gases and aerosols into the atmosphere disrupt the Earth's energy balance between absorbed sunlight and emitted thermal radiative energy, with a net effect of causing the Earth's surface and atmosphere to warm. The additional energy being added to the system by humans, previously estimated by models, has now been inferred by [Kramer et al. \(2021\)](#) using space-based observations, specifically 16 years of measurements from CERES and Atmospheric Infrared Sounder (AIRS) instruments aboard the Aqua satellite. They used a new technique to parse out how much of the total energy change is caused by humans, finding that 0.5 Wm^{-2} have been added from 2003 to 2018. This increase was primarily due to anthropogenic greenhouse gas emissions from such processes as power generation, transport, and industrial manufacturing, and secondarily because of reduction in reflective aerosols.

[Cherian and Quaas \(2020\)](#) compared regional trends in model-simulated aerosol optical depth (AOD) and cloud radiative effects from the Fifth and Sixth Coupled Model Intercomparison Projects (CMIP5 and CMIP6) with MODIS and CERES observations. The model results are broadly consistent with satellite retrievals in most parts of Europe, North America (NAM) and India. CMIP6 models match both the satellite-derived AOD upward trend in western NAM and the upward trend in eastern China where CMIP5 models fail, pointing to improved anthropogenic aerosol emissions in CMIP6. Drop concentration trends in both observations and models qualitatively match AOD trends. The study finds good agreement in regional solar cloud radiative effect trends, but this is largely due to compensating errors in cloud trends in the models.

Multi-angular polarimeter and radar instruments were used by [Sinclair et al. \(2021\)](#) to investigate how droplets in stratocumulus cloud top relate to rainfall that occurs lower in the cloud. They found a pattern in droplet sizes is related to rainfall formation and investigated how key cloud properties can be used to determine rainfall rates and will help improve the accuracy of future spaceborne cloud property retrievals.

[Stephens et al. \(2021\)](#) used AVIRIS FIREX-AQ data and retrievals were to demonstrate the value of an imaging spectrometer for the Decadal Survey's A-CCP Designated

Observable mission, currently in formulation as the Atmospheric Observation System (AOS).

Smoke layers and particle properties from wildfires

The conditions that modulate the partitioning of black carbon (BC) and brown carbon (BrC) formation from wildfires are not well understood. [Junghenn Noves et al. \(2020\)](#) combined *in situ* data from the NASA-NOAA FIREX-AQ aircraft field campaign in 2019 with data from MISR to constrain particle size, shape, light-absorption, plume height, and associated wind vectors. For the Williams Flats Fire plume on 6 August 2019, the MISR-retrieved particle properties indicate that the plume contained fine, highly absorbing, BC-like aerosols near the source, whereas downwind, the plume tends to show a systematically increasing amount and fraction of weakly absorbing, less BC-like aerosols. The MISR observations are relatively well supported by near-coincident FIREX-AQ *in situ* observations and provide greater context for the observed particle properties, enabling a more complete picture of wildfire plume mechanics and particle aging.

B. Tropospheric composition, air quality and COVID-19 impacts

Research supported by the Tropospheric Composition Program (TCP) and other ACFA programs, together with a range of space-borne missions and sub-orbital projects and field programs, is focused on the changing composition of the troposphere and the processes that impact air quality, particularly on regional scales. This work resulted in more than 60 publications in the last year, and in this section we summarize 6 papers related to measurements of trace gases that affect air quality and impacts of COVID-19 shutdowns.

Measurements of NO_x, ozone, and CO

[Gaudel, A. et al. \(2020\)](#) analyzed a long-term record of ozone measured from commercial aircraft at many locations across the globe. The showed that ozone has increased in 11 study regions widely distributed across the Northern Hemisphere since the mid-1990s, consistent with the OMI/MLS satellite product. In five geographic regions, much larger positive trends were found in the lower troposphere than in the free troposphere, while three regions where lower tropospheric ozone remained largely unchanged over the study period, consistent with reductions of ozone precursors in North America.

The Measurement of Pollution in the Troposphere (MOPITT) and TROPospheric Monitoring Instrument (TROPOMI) are two of only a few satellite instruments to derive carbon monoxide (CO) from solar-reflected radiances. Therefore, it is particularly important to understand how these two datasets compare. [Martínez-Alonso et al. \(2020\)](#) analyzed TROPOMI CO data acquired between November 2017 and March 2019 with respect to MOPITT as well as and airborne datasets to better understand TROPOMI's contribution to the global tropospheric CO record from 2000 to the present. The results indicate that TROPOMI CO retrievals over land show excellent agreement with respect

to MOPITT: relative biases and their standard deviations are on average $-3.7\% \pm 11.5\%$, $-2.2\% \pm 12.4\%$, and $-3.2\% \pm 11.1\%$ compared to the MOPITT thermal infrared (TIR), near-infrared (NIR), and multispectral (TIR + NIR) products, respectively. Temporal and spatial patterns in the data the two from TROPOMI and MOPITT also show good agreement.

[Judd et al. \(2020\)](#) evaluated Sentinel-5P TROPOMI v1.2 NO₂ tropospheric vertical columns (TrVC) during the Long Island Sound Tropospheric Ozone Study (LISTOS) in June-September 2018 using data from airborne mapping spectrometers and a network of ground-based Pandora spectrometers. They found that the satellite TrVCs are biased low by 19%–33% relative to the Pandora and aircraft measurements. Of this, 12-14% is driven by coarse *a priori* profile input in contrast to a high bias of 4-11% due to cloud parameter impacts during cloud free scenes. This highlights the utility of combining information from Pandora spectrometers and airborne spectrometers to separate influences of multiple *a priori* factors in retrieval evaluation as well as provide confidence in TROPOMI measurements.

Impacts of COVID-19 shutdowns on air quality

Lockdowns during the COVID-19 pandemic provided an unprecedented opportunity to examine the effects of human activity on fine particulate matter (PM_{2.5}). [Hammer et al. \(2021\)](#) used multiple NASA satellite aerosol products (from both MODIS and MISR) to help create maps of PM_{2.5} concentrations for January to April 2020 as compared to the same periods in 2018 to 2019. They estimated changes in population-weighted mean PM_{2.5} concentrations during the lockdowns of -11 to $-15 \mu\text{g m}^{-3}$ across China, $+1$ to $-2 \mu\text{g m}^{-3}$ across Europe, and 0 to $-2 \mu\text{g m}^{-3}$ across North America. They linked PM_{2.5} changes to a combination of meteorology and emission reductions such as transportation.

[Steinbrecht et al. \(2021\)](#) reported that in spring and summer 2020, ozone stations in the northern mid-latitudes, including stations in the Network for Detection of Atmospheric Composition Change (NDACC), recorded unusually low ozone in the free troposphere. From April to August, and from 1 to 8 kilometers altitude, ozone was on average 7% below the 2000–2020 climatological mean. Such low ozone, over several months, and at so many stations, has not been observed in any previous year since at least 2000. The observed anomaly is consistent with recent chemistry-climate model simulations, which assume emissions reductions similar to those caused by the COVID-19 crisis. COVID-19 related emissions reductions appear to be the major cause for the observed reduced free tropospheric ozone in 2020.

[Miyazaki et al \(2021\)](#) investigated the response of tropospheric ozone to the unprecedented reductions in NO_x emissions from the worldwide COVID-19 lockdowns. Anthropogenic NO_x emissions dropped by at least 15% globally and 18 to 25% regionally in April and May 2020, which decreased free tropospheric ozone by up to 5 ppb, consistent with TROPES satellite observations. The global total tropospheric ozone burden (TOB) declined by 6 TgO₃ (~2%) in May and June 2020 and was largely due to emission reductions in Asia and the Americas that were amplified by regionally

high ozone production efficiencies (up to 4 TgO₃/TgN). By comparison, the most aggressive representative concentration pathway (RCP) defined for the Climate Model Intercomparison Project-5 (RCP 2.6) projects a reduction of (TOB) of about 4% by 2030.

C. Greenhouse gas sources and emissions

The Carbon Monitoring System (CMS) and the OCO Science Team programs support research into the emissions and fluxes of CO₂, methane (CH₄) and nitrous oxide (N₂O) involving data from the NASA OCO-2 satellite and OCO-3 on the International Space Station (ISS) as well as a variety of other platforms including, increasingly, small satellites. These observations also underpin observations and modeling of the carbon cycle by NASA-supported researchers (see Section 1.1.9.1 below). Six of the most significant papers from the last year are summarized here. Additional work related to the carbon cycle is reported by the Carbon Cycle and Ecosystems Focus Area in Sections 1.1.8.2 and 1.1.8.2.

Anthropogenic carbon dioxide (CO₂) emissions dominate uncertainties in the global carbon budget. Of particular interest are better estimating point-source emissions such power plants and methane leaks occurring in oil and gas well fields. [Nassar et al. \(2021\)](#) use estimates of the column averaged dry air mole fraction, XCO₂, from OCO-2 to determine how well these measurements can quantify the CO₂ emissions from individual medium and large power plants and other large point sources. For eight, well-characterized power plants in the U.S., the emissions estimates from OCO-2 data were within 15% of those reported by the Environmental Protection Agency (EPA). These experiments also show the value of multiple revisits and highlight the challenges posed by multiple, nearby point sources.

In addition to observations from OCO-2 and OCO-3, there is a growing number of measurements available from airborne as well as small satellite instruments. [Cusworth et al. \(2021\)](#) demonstrate that quantitative retrieval of individual CO₂ plumes from large power plants around the world can be achieved using high-spatial resolution remote sensing observations from relatively low-spectral resolution observations available from the airborne AVIRS-NG and GAO instruments and the PRISMA satellite. Their calculated emissions rates scale with reported values for US powerplants, showing that the space-based data correctly capture day-to-day variability in power plant emissions, although there is an ~20% bias relative to the observations and metrics reported from continuous emissions monitoring systems (CEMS) that is yet to be understood. This work provides high confidence that global powerplant emissions can be effectively monitored from space and opens up the opportunity to quantify oil & gas supply chain emissions when coupled with methane plume monitoring (already demonstrated for multiple CH₄ emissions sectors).

Incidents involving loss of control of oil/gas wells can result in large but variable emissions whose impact on the global methane budget is currently unknown. [Cusworth et al. \(2020\)](#) combined satellite observations at different spatial and temporal scales to quantify emissions during a 20-day event in Texas. Their multi-satellite synthesis

captures both the short-term dynamics and total integrated emissions of the blowout, a level of detail previously not possible from space and difficult to do with surface measurements. Blowouts occur across the globe and multi-satellite observations can help to determine their pervasiveness, enable corrective action, and quantify their contribution to global methane budgets.

[Barkley et al., \(2021\)](#) showed that central and eastern U.S. methane emissions from oil and gas production activities are at least a factor of 1.5 to 1.8 times higher than those reported by the EPA. While the finding that EPA inventories underestimate methane emissions is not new, the method and extent of their study, provides powerful new independent evidence that prior findings are correct. The study takes advantage of the largest airborne ethane data base collected to date across multiple years and seasons and uses ethane as a unique tracer of oil and gas methane emissions. It also encompasses multiple gas basins at one time with observations that accumulate emissions days downwind of oil and gas production areas.

While OCO-2 retrieves CO₂ data in regularly-repeating narrow swaths, OCO-3 can do multiple swaths over selected regions. [Kiehl et al. \(2021\)](#) are the first to describe results OCO-3 special sampling, snapshot-area maps (SAM) which are designed to collect detailed spatial information on CO₂ over regions on the scale of 50 miles by 50 miles. The SAMs highlight the CO₂ enhancements, typically about 2 ppm, over Los Angeles relative to desert regions to the northeast. Variations in the magnitude and location of enhancements are largely explained by variations in the wind speed and direction. The work also highlighted the fact that OCO-3 SAMs observe about three times the fraction of emissions from the city compared to the OCO-2 validation sampling over the region.

Atmospheric Carbon and Transport – America (ACT-America) is an Earth Venture Suborbital (EVS) project that has developed a strategy to capture emissions over large regions by using weather fronts as gathering mechanisms. Following this approach, [Eckl et al. \(2021\)](#) used airborne lidar measurements of nitrous oxide (N₂O) to estimate regional agricultural emissions over the upper Midwest in the fall of 2017 and summer of 2016. They found that emissions from Midwest agricultural systems were three- to six times higher than inventory estimates in fall of 2017, and 9 to 11 times higher than inventory estimates in the summer of 2019.

D. Stratospheric composition change & ozone depletion

The ACFA Upper Atmosphere Research Program (UARP) and its associated space-borne missions, airborne campaigns and ground-based observational networks support the international effort to understand the recovery of ozone and the concomitant impacts of a changing stratospheric composition. This effort has come increasingly to involve research into the effects of smoke injections into the upper troposphere and lower stratosphere (UTLS) from pyroCbs as well as volcanoes. We highlight in this section 8 papers from the last year on the topics of ozone depleting substances, emissions and trends, UTLS aerosols, and measurements of upper atmosphere composition change.

Ozone depleting substances, emissions and trends

CFC-11 was widely used in refrigeration and in blowing agents for polyurethane foam insulation and was included in the regulations put forward by the 1987 Montreal Protocol because of its role in stratospheric ozone depletion. [Chen et al. \(2020a\)](#) used data from four channels of the hyperspectral Atmospheric Infrared Sounder (AIRS) on the Aqua satellite to show a slowdown of the decline in atmospheric chlorofluorocarbon-11 (CFC-11) concentrations over the period 2003-2018. The data cover low and mid-latitudes, from 55°N to 55°S.

This global slowdown was related to an unexpected illegal increase in CFC-11 emissions beginning in 2013, reported in two papers in *Nature* in 2018 and 2019. Much of this was attributed to emissions from two provinces in eastern China. As [Park et al. \(2021\)](#) now report, emissions since 2018 for those two provinces appear to have returned to pre-2013 levels. These results were based on more recent hourly CFC-11 measurements from the Advanced Global Atmospheric Gases Experiment (AGAGE) stations in Gosan, South Korea and Hateruma, Japan used in conjunction with atmospheric chemical transport models. It thus appears that a substantial delay in ozone-layer recovery has been avoided, perhaps owing to the above timely reporting.

Measurements from 10 AGAGE stations and archived air samples were used in a paper by [Gressent et al. \(2021\)](#) who deduced a 6-fold increase in emissions of sulfuryl fluoride (SO₂F₂) between 1978 and 2019. SO₂F₂ is a powerful greenhouse gas and has replaced the fumigant methyl bromide, now banned under the Montreal Protocol. Using a hybrid regional modeling approach to estimate the spatial distribution and trend in SO₂F₂ emissions between 2000 and 2019, the authors deduce that the global emissions increase is driven by the growing use of this gas in structural fumigation in North America and in post-harvest treatment of grains and other agricultural products worldwide.

Chlorine monoxide (ClO) lies at the center of the photochemistry of ozone loss but is a significant measurement challenge, particularly in the upper stratosphere. [Nedoluha et al. \(2020\)](#) presented the first year of ClO and O₃ measurements from a new 278 GHz Chlorine monOxide Experiment (ChlOE) microwave instrument on Mauna Kea and compared them to Aura-MLS O₃. The ChlOE instrument can, in good local conditions, provide continuous measurements at any time of day, and they are therefore able to sample the full diurnal cycle; it also allows for the simultaneous measurement of ozone, which helps to provide a useful calibration check. ChlOE measurements compare well (within ~6–8%) with the twice-daily measurements from the Aura Microwave Limb Sounder and will extend the ClO measurements time series from which trends have been calculated since 1995.

UTLS aerosols, volcanoes and pyroCbs and climate impacts

The increase of intensity and frequency of wildfires since 2017 has become an important societal issue, as aerosols have a significant radiative impact on the troposphere and

stratosphere. Furthermore, they play an important role in heterogenous polar ozone chemistry.

Recent fire seasons have featured volcanic-sized injections of smoke aerosols into the stratosphere where they persist for many months. [Christian et al. \(2020\)](#) employed the space-based Cloud Aerosol Transport System (CATS) and CALIOP lidar to track the evolution of the stratospheric aerosol plumes resulting from the 2019–2020 Australian bushfire and 2017 Pacific Northwest pyrocumulonimbus events and then compared them to two volcanic events: Calbuco (2015) and Puyehue (2011). They found that the pyrocumulonimbus and volcanic aerosol plumes evolved distinctly, with pyrocumulonimbus plumes rising upwards of 10 km after injection to altitudes of 30 km or more, compared to small to modest altitude increases in the volcanic plumes.

The Raikoke volcanic eruption occurred on June 21, 2019 with ash ejected to the upper troposphere and lower stratosphere, and the London Volcanic Ash Advisory Centre (VAAC) provided initial estimates of the plume arrival over the UK in early July. [Osborne et al. \(2021\)](#) examine the dispersion of the Raikoke volcanic plume and its impact over the UK and Europe. They document a methodology for identifying and distinguishing between volcanic ash plumes and PyroCb smoke using the Met Office Numerical Atmospheric-dispersion Modelling Environment (NAME) and observations from the UK Met Office lidar network and NASA MPLNET. The MPLNET data provided plume monitoring upwind of the UK and Europe receptor region, including data from Fairbanks Alaska, and NASA GSFC. Coupling the MPLNET data coupled with the NAME model output and lidar observations from the UK provided sufficient information to identify and distinguish the volcanic plumes from the smoke. The study demonstrates the utility of using different lidar networks to provide operational monitoring at regional and global scales, one of the goals of the WMO GAW Aerosol Lidar Observation Network (GALION) of which MPLNET is a core member.

Upper atmosphere composition change: Measurements and observations

Ozonesondes are a stable reference for the global ozone observing network, making inexpensive, accurate measurements of ozone from the ground to 30km, with high vertical resolution, for more than 50 years. Ozonesonde data are used extensively for validation of satellite ozone measurements, models, and for trend analyses. [Tarasick et al. \(2021\)](#) reviewed the current state of knowledge of ozonesonde uncertainty and bias and present a systematic approach to quantifying these uncertainties by considering the physical and chemical processes involved. While ozonesonde precision has improved through the adoption of strict standard operating procedures, additional improvement is possible with further research, toward a goal of less than 5% overall uncertainty throughout the global network.

[Steiner et al. \(2020\)](#) calculated temperature trends in the troposphere and stratosphere from the latest available observational records, which include two US-based and one European NDACC lidars (TMF, MLO, and OHP). The authors focus on assessing climate trends and identifying the degree of consistency among the observational

systems. They found that over the 40-year period, the stratosphere cooled some 1–3 K. Over the same period, the troposphere warmed 0.6–0.8 K, and radio occultation measurements available since 2001 indicate tropospheric warming trend of 0.25–0.35 K per decade. Amplified warming in the tropical upper-troposphere compared to surface trends for 2002–2018 is in approximate agreement with moist adiabatic lapse rate theory, and the consistency of trend results from these upper-air data sets will help to improve understanding of climate changes and their drivers.

E. International Activities

Committee on Earth Observation Satellites, Atmospheric Composition - Virtual Constellation

The Committee on Earth Observation Satellites (CEOS) was established in 1984 to coordinate civil space-borne observations of the Earth. The 61 participating agencies strive to enhance international coordination and data exchange and to optimize societal benefit.

In support of the Group on Earth Observations (GEO) objectives and as a space component of the Global Earth Observation System of Systems (GEOSS), the CEOS Atmospheric Composition Virtual Constellation ([AC-VC](#)) aims to collect and deliver data to improve monitoring, assessment and predictive capabilities for changes in the ozone layer, air quality and climate forcing associated with changes in the environment through coordination of existing and future international space assets. The AC-VC chairs are from ESA, NASA, and NIES-Japan, and many NASA researchers lead and participate in its diverse activities.

In the past year, the AC-VC Greenhouse Gas (GHG) Roadmap and Project continued the implementation of its CEOS leadership-endorsed white paper, [A Constellation Architecture for Monitoring Carbon Dioxide and Methane from Space](#), supporting activities that included the combination of bottom-up and top-down inventories to support the global stock take and piloting global top-down inventory products. These activities were discussed at the June 2021 virtual AC-VC meeting. The meeting also focused on initial results and validation activities from the South Korean Geostationary Environment Monitoring Spectrometer (GEMS) instrument. Preparations for the validation and development of common products for the NASA TEMPO and European Sentinel 4 missions continued. Planning and implementation of a new AC-VC work program activity, Tropospheric Ozone Dataset Validation and Harmonization, was also reviewed. This new activity is leveraging synergies between AC-VC and the international Tropospheric Ozone Assessment Report (TOAR-II) initiative. The production of peer-reviewed papers on intercomparisons and harmonization of tropospheric column ozone datasets is envisaged.

Section 1.1.8.2 Carbon Cycle and Ecosystems Focus Area

The research conducted in the Carbon Cycle and Ecosystems focus area continues to be groundbreaking and is critical for characterizing the functioning of the Earth System across land and water. Ground-based, suborbital and satellite observations are used to further the understanding of Earth's ecosystems and biogeochemical cycles, and how naturally and human-induced forcings may change them. The scope of the research that is undertaken by the Carbon Cycle and Ecosystem Focus Area can be local, regional, or global in footprint. The data collected are also essential to improve satellite retrievals, and for advancement of modeling activities of aquatic and terrestrial ecosystem processes and dynamics that enable diagnosis of the factors responsible for current ecosystem states and prediction of future states. Selected research results and other accomplishments of the 2021 fiscal year are highlighted below.

Contributions from the Carbon Cycle and Ecosystems Focus area to Annual Performance Indicator 1.1.8 provided new insights into aquatic and terrestrial ecosystems, including structure (e.g., community composition, biomass, health), extent (e.g., forest cover change), biodiversity, and function (e.g., carbon export, interactions between global warming and fire, carbon storage, and human impacts), further advancing the use of remote sensing to better understand the Earth system.

Ocean Biology and Biogeochemistry

Water is a critical element for life, and water quality is an important metric for human health, activity, and recreation. Water quality is affected by a variety of natural and anthropogenic drivers, and understanding how water quality changes, how fast, and where these changes occur, is of utmost importance for ecosystem management and economic activities. Satellite remote sensing has been a critical tool for observing changes in water quality near coastal regions, and more recently inland thanks to increased spatial resolution, but the advent of hyperspectral sensors promises to enhance the accuracy of remotely sensed in-water products, thereby providing more precise retrievals of in-water constituents. For example, Pahlevan et al. (2021) determined that retrievals of phytoplankton absorption using hyperspectral sensors may be two-to-three times more precise than those done through heritage (multispectral) ocean color algorithms. This would help characterize more precisely organisms such as those producing harmful algal blooms (HABs), and better quantify biodiversity in aquatic ecosystems. Harringmeyer et al (2021) further noted that for water quality applications, it will be very useful to measure via satellite remote sensing the ultraviolet (UV)-visible range, much like the upcoming Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) and the Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR) missions will do. Information in the UV region will help detect organic matter in optically complex waters located in coastal, estuarine, and inland areas, which will open new possibilities for water quality management, and signify a leap forward for quantification of organic carbon dynamics in ocean margins. Models are also critical to study the impacts of nutrients and sediments from runoff on water quality. For example, Kim et al. (2020) further explored the relationship between temperature and water clarity and highlighted the importance of adequate representations of these parameters in models of

estuarine and coastal water quality. Similarly, Moriarty et al. (2021) applied a biogeochemical model to study how sediment transport and resuspension in the Chesapeake Bay can reduce photosynthesis and increase remineralization, leading to less oxygen and more ammonia in the water, which impacts the biology of the bay, the organisms living there, and consequently may lower water quality. The study of water quality via remote sensing hinges on the understanding of the optical signal emerging from the water bodies; to adequately interpret these signals, and further capitalize on their information, it is important to advance research on both in situ and remotely observed light-water interactions. The light signal emerging from water contains many dimensions of information, including both color and polarization. These properties of light can be measured by spectrometer and polarimeter instruments that NASA has deployed onboard satellites, including the upcoming PACE mission. Koestner et al. (2020) revealed that the polarization signal of light can be used to characterize size and composition of natural particle assemblages of seawater. Additionally, Lange et al. (2020) demonstrated that, when used in conjunction with hyperspectral data, like the upcoming PACE mission will provide, retrieval algorithms for cell abundances of *Prochlorococcus*, *Synechococcus*, and autotrophic picoeukaryotes performed well compared to in-water measurements from six Atlantic Meridional Transect research cruises. Furthermore, Hooker et al. (2021) developed a novel technique to smoothly transition ocean color retrievals from the open-ocean to the more complex and sediment-laden waters in coastal regions and estuaries. These are all critical advances in the use of optics to study biogeochemical processes of the Earth's oceans.

One important biogeochemical component is carbon, and the EXPORT Processes in the Ocean from Remote Sensing (EXPORTS; Siegel et al., 2021) project is collecting critical information for quantifying the export and fate of upper ocean net primary production using satellite observations and state of the art ocean technologies. For example, Roca-Martí et al. (2021) used data from the 2018 EXPORTS field campaign to quantify particulate carbon fluxes and remineralization scales more accurately, revealing that transfer efficiencies vary based on the types of particles present. Their work critically advances the understanding of how phytoplankton community composition and food-web dynamics relate to what kind and how much organic material sinks to deeper waters. Similarly, Stamieszkin et al. (2021) used the novel data collected during the 2018 EXPORTS field campaign to assess how zooplankton fecal pellets sink from the sea-surface and contribute to the biological carbon pump. This is an important study since different sizes of zooplankton generate different fecal pellet sizes, which directly relate to sinking rates, an aspect of particulate organic carbon export that has never been directly measured. EXPORTS employed state of the art in situ technology to study carbon export pathways and dynamics, and this type of sampling approach is of particular importance in areas hard to access, like the Southern Ocean. In the Southern Ocean, floats and gliders represent critical means of obtaining biogeochemical information on ocean biology and the biogeochemical mechanisms that drive the oceanic carbon cycle. Arteaga et al (2021) used floats (BGC-Argo) to examine how the annual phytoplankton biomass varies in the Southern Ocean and found that the productivity of the region can be highly sensible to perturbations, as it is uniquely influenced by a variety of processes that act differently than in other areas of the ocean. In addition, not all areas of the Southern Ocean behave

equally when it comes to absorbing or emitting carbon dioxide. Schultz et al (2021) used a model to quantify the effects of sea ice on biological productivity and dissolved inorganic carbon in the West Antarctic Peninsula (WAP) and found that, depending on the extent of sea ice, the WAP can take up atmospheric carbon dioxide at different rates. Both studies vastly improve our knowledge and reduce uncertainty surrounding the fate of carbon in the Southern Ocean, a critical component of the global carbon cycle.

Terrestrial Ecology

Vulnerability and Resilience of Northern Ecosystems

High latitude regions, such as the Arctic-Boreal Region (ABR), contain some of the most rapidly changing and vulnerable ecosystems on Earth. They also play an important role in the global carbon (C) cycle, and whether they act as future net C sinks or sources depends on the feedbacks between ecosystems and a changing climate. Analyses from the Arctic Boreal Vulnerability Experiment (ABoVE) continue to provide an enhanced understanding of how key ecological properties are changing across space and time, and how these changes impact the Earth system. For instance, while climate change is altering disturbance dynamics in boreal forests (the largest forest biome on the planet), the impact of these changes on boreal forest C budgets is not well understood. In a recent study, Wang et al. (2021) leveraged a time series of Landsat data in conjunction with ICESat lidar data to examine how disturbances have altered aboveground biomass (AGB), from 1984-2014, in boreal forests across Alaska and western Canada. They observed a net gain in AGB ($+434 \pm 176$ Tg), after accounting for reductions in AGB due to disturbances such as fire (-176 ± 99 Tg) and harvest (-42 ± 10 Tg). However, this observed gain in ABG is three times lower than those currently estimated via model inter-comparison projects, likely due to poor representation of fire in the models.

The increase in wildfire occurrence and severity seen over the past decades in the ABR is expected to continue in response to climate change. Recent studies documented positive trends in gross primary productivity (GPP; the amount of carbon fixed during photosynthesis) for Arctic boreal biomes driven by warming, but it is unclear how GPP trends are affected by wildfires. To assess this, Madini et al. (2021) leveraged satellite data in a modelling context to analyze ecosystem recovery from large fires in Alaska from 2000–2019. Their results confirmed the findings of earlier studies that demonstrated that warmer-than-average years provide favorable climate conditions for vegetation growth, leading to an increase in GPP. However, higher temperatures also increased the risk of wildfire occurrence leading to direct carbon loss over a period of 1–3 years. While mortality related to severe wildfires reduced ecosystem productivity, post-fire productivity in moderately burned areas showed a significant positive trend, which may maintain the region's net carbon sink into the future. This rapid GPP recovery following fires might be favorable for maintaining the region's net carbon sink, but wildfires can also promote the release of long-term stored carbon in deep organic soils. Despite an increase in the frequency of fires that burn more deeply into organic soils, a study by Mack et al. (2021) demonstrated that the carbon loss from boreal fires in slow growing black spruce forests was offset by the increased carbon uptake by fast growing deciduous trees that increase in dominance following fire. This carbon uptake was four to five times greater than the fire induced carbon losses over the 100-year disturbance cycle. This

study also suggests that reduced fire activity in future deciduous forests could increase the longevity of forest carbon storage on these landscapes.

Forest fires are usually viewed within the context of a single fire season, in which weather conditions and fuel supply can combine to create conditions favorable to fire ignition—usually by lightning or human activity—and spread. Some fires exhibit ‘overwintering’ behavior, in which they smolder through the non-fire season and flare up in the subsequent spring. In boreal forests, deep organic soils favorable for smoldering, along with accelerated climate warming, may present unusually favorable conditions for overwintering. However, the extent of overwintering in boreal forests and the underlying factors influencing this behavior have been unclear. Scholten et al. (2021) showed that overwintering fires in boreal forests are associated with hot summers generating large fire years (large annual burned area) and deep burning into organic soils, conditions that have become more frequent in recent decades.

Human Impacts on Terrestrial Ecosystems

Human activities can also have large impacts on ecosystems and associated biogeochemical cycles, especially when coupled with natural processes. In a recent study, Xu et al. (2021) estimated that although woody plants in forested savannahs globally are responsible for 80% of the land C sink, human induced deforestation emits an amount of C equal to about half of that emitted by burning of fossil fuels each year. However, replanting of trees and reestablishment of forests can offset a portion of these emissions. For example, Tang et al. (2021) leveraged a time series of MODIS data in conjunction with a carbon bookkeeping model to assess the impacts of land use/land cover (LULC) change on carbon emissions in the Mekong River Basin from 2001-2019. They found that the largest components of LULC change in the region are the establishment of plantations and agricultural expansion in previously forested areas. Although this land use conversion released carbon, carbon uptake from the establishment of new plantations offset almost half of those emissions, indicating that the assessment of post-deforestation land use is crucial for quantifying the short- and longer- term carbon consequences of LULC change.

Afforestation (establishment of new forests) and reforestation (reestablishment of forests) also have the potential to provide effective climate mitigation through forest C sequestration; they can also impact surface reflectivity. For example, Williams et al. (2021) leveraged forest biomass maps derived from remote sensing data in conjunction with forest inventory data to quantify the balance of carbon and albedo for forests across the US. They found that forest loss in the intermountain and Rocky Mountain West causes net planetary cooling but losses east of the Mississippi River and in Pacific Coast states tend toward net warming. This study highlighted the need to understand where reforestation and avoided deforestation could have the maximum effect and where they could be counterproductive prior to implementation. Similarly, Lamb et al. (2021) leveraged geospatial data and high-resolution remote sensing data to quantify economic opportunities for reforestation in the state of Maryland. They found that transitioning agricultural lands with high carbon sequestration potential to forests would be more profitable on 23% of cropland in Maryland.

Other human activities such as livestock production and the creation and maintenance reservoirs for water storage also have significant impacts on the global carbon budget through the production and emission of methane (CH₄). For example, Johnson et al. (2020) integrated several geospatial (SRTM derived water body data) and remote sensing datasets (MODIS, AMSER-E) along with field-based CH₄ flux measurements into a modelling framework to estimate reservoirs-based CH₄ emissions across the Globe. They found that Global reservoir area is $297 \times 10^3 \text{ km}^2$, with mean CH₄ emissions of 10.1 Tg yr^{-1} , approximately equivalent to one third of annual CH₄ emission from biomass burning. The new datasets and methodologies derived in this study provide a novel framework to better understand and model the current and future role of reservoirs in the global CH₄ budget, and to guide reservoir-related CH₄ emission mitigation efforts. In another study, Yu et al. (2021) collected multi-seasonal airborne measurements of CH₄ and related gas species across the Upper Midwest, and leveraged a high-resolution inverse model to quantify regional CH₄ sources. They found that natural wetlands are the largest regional CH₄ source (20 Tg yr^{-1}), with livestock being the largest anthropogenic source (15 Tg yr^{-1}). Their results confirm the important influence of intensive animal agriculture on regional CH₄ emissions, and imply that substantial CH₄ emission mitigation opportunities exist through improved livestock management.

Land Cover and Land Use Change

Deforestation and Forest Degradation

Forests in South/Southeast Asia (S/SEA) are undergoing rapid changes due to increased population and economic development. Land-use/cover changes (LUCC) in the forestry sector has significant impact on environmental change in S/SEA. A recent study on forest land cover changes in Central India by DeFries et al., (2021) suggests that improved household living standards can restore dry tropical forests. The authors highlighted that durable housing and alternatives to fuelwood for cooking are critically needed for reducing multi-dimensional poverty. In a related study, Biswas et al., (2021) analyzed the effects of political transition and subsequent timber bans on forest loss in Myanmar. Results show that at the national level, the political transition in 2011 had maximum effect on forest loss while the timber bans decreased forest loss almost three-fold during 2015-2017. The dominant drivers of change shifted from organizing plantations in 2011 to infrastructure development in 2015. This study demonstrates the effects of policy on forest loss at various scales and can inform decision-makers on forest conservation, planning and development of mitigation measures. S/SE regional activities included publication of a special issue “Forest Land Use Cover Changes (LUCC) and Impacts on Environment in South/Southeast Asian Countries,” led by Vadrevu et al. (2021) in the *Forests* journal. Nine different articles, published by international research teams, highlight such forest changes as deforestation, logging, reforestation, etc. Drivers vary widely within the region and include economic development, government policies, international trade, improper forest management, and land tenure issues. These socioeconomic factors, along with variability in weather and climate, contribute to forest changes. This special issue contributes to the NASA LCLUC program-funded South/Southeast Asia Research Initiative (SARI).

Spatial time-series measurements of forest degradation rates are important for estimating national greenhouse gas emissions but have been challenging for open forests and woodlands. This lack of quantitative data on forest degradation rates, location and biomass is an important constraint to developing national REDD+ policy. In Malawi, and in most countries in Africa, most assessments of forest cover change for carbon emissions monitoring tend to report only deforestation in the public forest estate managed by the government, even when important forest degradation also occurs in agricultural areas, such as customary forests and other tree-based systems. Skole et al. (2021) developed a new robust forest map for Malawi, and spatial and quantitative measurements of both forest degradation and deforestation. That study also demonstrated the usefulness of their approach through the introduction of a tool that maps trees outside of forests. The results produced new estimates of landscape-wide deforestation and forest degradation rates between 2000–2009 that can be used to support REDD+ National Forest Monitoring Systems. For the Brazilian Amazon, Matricardi et al. (2020) generated a long-term spatially quantified assessment of forest degradation from 1992 to 2014. They measured and mapped the full range of activities that degrade forests and evaluated the relationship with deforestation. Forest degradation is a separate and increasing form of forest disturbance, and the area affected is now greater than that due to deforestation.

Mining and Migration

The mining sector has served as a main pillar of the economy in Mongolia during both the socialist period before 1991 and the current free-market economy. The government conversion of pastoral areas to mine extraction aggressively increased after 1990, assuming that mining activity would support the local labor market and boost the local economy, thereby attracting more migrants. Following a conceptual framework of the changes in rural and urban populations in Mongolia using the 2010 workforce survey data, Amartuvshi et al. (2021) constructed models to empirically examine migrations among non-mine country districts, urban places, and mining districts. The article highlights that Ulaanbaatar, a capital city, and Erdenet, a huge mine during the socialist era, remain attractive places for migration. New mining sectors appear not to improve employment among local herding communities. Migration has become an adaptation strategy in response to economic transition and changing climate in arid Mongolia. Xu et al. (2021) reviewed migration in Mongolia from the early 2000s to the mid-2010s. The results suggest that urbanization accounted for over 80% of all migration, mainly into Ulaanbaatar's capital city, where nearly 70% of recent population growth was from migration. Migratory rates to urban and rural areas increased during 2011–2014 following a severe disaster - the 2009–2010 severe winter in which many livestock died, primarily due to starvation. People from the eastern region were more likely to move back to the rural area than those living in the western region as the east had a more favorable climate for pastoralism. The results confirm the importance of climate and weather changes in migration along with several socio-economic indicators.

Biodiversity

Advances in Detection of Biodiversity Patterns

Advances in remote sensing have allowed for new means of detecting the role biological diversity plays in Earth system processes. For instance, using newly available

evapotranspiration data from ECOSTRESS, Poulos et al (2021) showed that plant species composition drives post-fire evapotranspiration patterns and is likely to continue to play critical roles in shaping post-fire plant communities and forest water cycling under future environmental change. Using newly available GEDI Lidar data, Fagua et al (2021) revealed a strong relationship between canopy structure and tree diversity, providing support for ecological theories that link structure to diversity via niche partitioning and environmental conditions. These methods could be applied to assess tree diversity of any tropical forest. In preparation for future hyperspectral satellite missions (e.g., PACE, SBG), Meireles et al (2020) showed that leaf spectra capture the phylogenetic history of seed plants and the evolutionary dynamics of leaf chemistry and structure. Consequently, spectra have the potential to provide breakthrough assessments of leaf evolution and plant phylogenetic diversity at global scales.

Demonstrating Impact of Humans on the Environment

The capability to understand the impact humans have on the environment has never been more necessary as such impacts on global biodiversity continue to mount. For example, extreme weather events are increasing in frequency and intensity because of climate change. Cohen et al (2021) compiled data from eBird, a global citizen science initiative, to examine how 41 eastern North American birds shifted their occurrence and abundance patterns immediately following two recent extreme weather events, the intrusion of a polar vortex and a winter heat wave. Following the polar vortex, population density was temporarily reduced. Inversely, bird density increased after the heat wave. This kind of research is critical to better quantify the broad-scale sensitivity of different species to multiple types of extreme weather events as climate change progresses and climatic variability increases. Another type of impact is light and sound contamination, which can alter the behavior and reproduction of many species. Ditmer et al (2020) used VIIRS data to assess the effects of light exposure on mammal behavior and predator–prey relationships across wildland–urban gradients in the southwestern United States. Using radio collar data for cougars and mule deer, and the locations of cougar-killed deer, they found that urban deer are more active at night than their wildland conspecifics. However, cougars killed deer at the wildland–urban interface, leveraging the darkest locations in urban areas to mask their approach to deer. Senzaki et al (2020) analyzed surveyed bird behavioral data and showed that reproduction for many species of birds is negatively impacted by the introduction of artificial light and sound. In addition, Ditmer et al (2021) showed that light pollution fragments most mammal ranges in the continental United States. These impacts are widespread and underscore the influence of human-induced forcings on the Earth System.

Applying Remote Sensing Capability to Environmental Decision Making

Scientific research underpins decision-making, and satellite tools are critical for many of these applications, as they can frequently cover broad areas of the Earth, collecting critical data that helps better understand the Earth System. For example, Woodill et al (2020) combined vessel location data with remotely sensed oceanographic variables to build a model capable of predicting whether a fishing vessel is fishing within protected waters off the coast of Argentina. This work offers a promising step towards preempting illegal activities, rather than reacting to them forensically. To better define and constrain

forests of high ecological value, Hansen et al (2020) mapped locations high in forest structural integrity as a measure of ecological quality based on recently developed fine-resolution maps of three-dimensional forest structure, integrated with human pressure across the global moist tropics. Their work shows that most of the pristine forests, which are of high ecological value, have no formal protection and provide a policy-driven framework for conservation and restoration.

Assessing the value of ecosystem services is also an important way to track the benefits ecosystems provide to humans. For example, Heris et al (2021) developed a model leveraging remote sensing inputs to estimate the energy savings for indoor cooling as a result of trees mitigating heat and intercepting rain. Similarly, Kowal et al (2021) modeled the interacting effects of land protection on Mongolia's rangeland and future livestock production. These capabilities will demonstrate the benefit of environmental protection with impact on the lives and livelihoods of people across the globe. In addition, it has been recognized that Indigenous Traditional Knowledge (ITK) can promote the conservation of biodiversity; O'Bryan et al (2020) conducted the first comprehensive analysis of terrestrial mammal composition across mapped Indigenous lands and found that 60.4% of all assessed species had at least 10% of their habitat on Indigenous lands, with 22.6% having over 50%, marking these lands as critical to conservation efforts. These results underline the necessity of partnerships with Indigenous Peoples to increase knowledge and maintain biodiversity.

Airborne and surface-based activities

Airborne and surface based (field) activities were severely impacted by the COVID-19 pandemic. In particular, travel restrictions, social distancing, and institutional closures resulted in cancellations and delays of deployments scheduled for the FY21.

EXPORTS

EXPORTS was perhaps one of the few field campaigns that was able to take place during FY21. Postponed from FY20 due to the pandemic, the EXport Processes in the Ocean from Remote Sensing (EXPORTS) North Atlantic field campaign sailed May 1st, 2021, from Southampton (UK) with the objective of characterizing the export and fate of upper ocean net primary production created by the North Atlantic spring bloom. The project utilized the National Oceanographic Centre's RRS James Cook and the RRS Discovery, and deployed over 45 autonomous platforms throughout their month-long field campaign. A third ship, the R/V Sarmiento de Gamboa (Spain), joined the EXPORTS field effort for half of the campaign as part of the Woods Hole Oceanographic Institution's Ocean Twilight Zone project, which has complementary objectives, thereby augmenting the sampling and footprint of EXPORTS. The EXPORTS North Atlantic experiment offered an opposite end member to the experiment conducted in North Pacific in 2018. While most of the scientific finding will be revealed over the next year as the science teams analyze their samples, early results (thanks to the wide array of autonomous vehicles deployed and remote sensing tools) suggest that the campaign was able to capture different stages of the North Atlantic Bloom and characterize different carbon export

pathways. EXPORTS data is anticipated to support the study of the oceanic carbon cycle for decades to come.

ABOVE

Field work for the Arctic-Boreal Vulnerability Experiment was curtailed significantly because of the COVID pandemic in 2021. The research team cancelled the UAVSAR and AVIRIS airborne campaigns due to logistical limitations placed on the field crew. Researchers compensated for these obstacles by limiting their field work to Alaska and by concentrating on analysis of existing data. ABoVE Phase 3, the third and final phase of ABoVE is being solicited in ROSES 2021, and we anticipate returning to airborne UAVSAR and AVIRIS airborne campaigns during the 2022 field season.

GEDI

GEDI cal-val flights using LVIS on the JSC GV aircraft occurred during July and August 2021. Flights concentrated on underflying existing GEDI orbits and overflying ground plots in French Guiana and Guyana as well as a range of sites in eastern North America. In addition, members of the GEDI Science Definition Team collected field measurements including ground-based LiDAR scans at the Coweeta Experimental Forest in North Carolina near the time of LVIS overflights. Decadal Survey Incubation component for the Surface Topography and Vegetation (STV) initiative was added to look at different signal to noise ratios, footprint sizes, and footprint densities on waveform and vegetation height retrievals. GEDI finished its prime mission in April 2021. It is now in extended operations.

Section 1.1.8.3 Climate Variability and Change Focus Area

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. These activities can be divided into those focused on characterizing the behavior of the Earth system (performance indicator 1.1.8), and those that focus on enhanced understanding and prediction (performance indicator 1.1.9).

It is useful to break the supported activities into four major categories:

- Sea Ice in the Climate System
- Land Ice in the Climate System
- Oceans in the Climate System
- Integrated Earth System and Modeling

Highlights of results published this past year related to the characterization of the behavior of the Earth system relevant to the CVC FA are summarized below:

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.

Sea ice extent and other Arctic sea ice properties and trends are 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.

As was the case last year, several significant papers were published in the last year using ICESat-2 to study sea ice properties, its thickness, and changes. Farrell et al. (2020) demonstrated for the first time with ICESat-2 that summer melt features on sea ice can be reliably detected from a spaceborne altimeter system. They showed that ICESat-2 is capable of providing highly precise measurements of sea ice surface roughness, pressure ridge height, and sea ice floe size distribution, resolving features as narrow as 7 m and achieving a vertical height precision of 0.01 m. Tilling et al. (2020) used ICESat-2 photon data and coincident high-resolution satellite imagery from WorldView-2 and

Sentinel-2 over different sea ice topographies to locate individual melt ponds on Arctic sea ice during the summer months. Sea ice melt ponds reduce both the reflective and insulative properties of sea ice, so determining their locations on sea ice is a critical observation for accurately calculating sea ice height and sea ice freeboard using laser and radar altimeters. They explored how sea ice melt ponds impact the return laser signal from ICESat-2's laser altimeter system and discussed how ICESat-2 data could be used in the future to retrieve measurements such as melt pond width, fraction and depth.

A study by Bagnardi et al. (2021) took a first look at high-resolution laser altimetry measurements made by ICESat-2, and the results were compared using near-synchronous data collected by ESA's CryoSat-2 radar altimeter collected as part of the CRYO2ICE orbit alignment campaign between the two satellites over the Arctic Ocean. The team found good agreement in the along-track sea surface height anomalies between the two instruments, as well as in the gridded monthly sea surface height anomaly estimates. These comparisons provide additional confidence to the polar oceanography community that ICESat-2 can be used to determine regional and seasonal polar sea surface height variability, in line with what CryoSat-2 has been known to provide for the past several years.

Comparisons between measurements taken by ICESat-2 and CryoSat-2 over sea ice were also made with data collected over the Southern Ocean and Antarctic coastal areas. Kacimi and Kwok (2021) offered the first examination of the ICESat-2 and CryoSat-2 sea ice freeboards, the snow depth derived from their differences, and the calculated sea ice thickness and volume. Their analysis spans an 8-month winter between 1 April and 16 November 2019, and characterized the behavior of the circumpolar ice cover in seven geographic sectors. They found that Antarctic snow depth estimates are highly correlated with ICESat-2 freeboards, with the ICESat-2 freeboard explaining > 90 % of the variance in snow depth. Their results suggest that more than 60 %–70 % of the ICESat-2 freeboard is snow. At the sector scale, the adjusted estimates seem to be more credible than a continent-wide estimate, although better assessment of these parameters awaits better field measurements.

The monitoring of summer sea ice trends in the Arctic Ocean remained a high-priority study area for NASA investigators this year. Schweiger et al. (2021) used a combination of satellite data and sea ice model experiments to determine the cause of a record sea ice minimum in August 2020 in the Wandel Sea near northeast Greenland (what is known as the "Last Ice Area"). In their model simulations, there was a multi-year sea-ice thinning trend due to climate change. Natural climate variability expressed as wind-forced ice advection and subsequent melt added to this trend. In spring 2020, the Wandel Sea had a mixture of both thin and—unusual for recent years—thick ice, but this thick ice was not sufficiently widespread to prevent the summer sea ice concentration minimum. With continued thinning, more frequent low summer sea ice events are expected. The results suggest that the Last Ice Area, an important refuge for ice-dependent species, is less resilient to warming than previously thought.

Land Ice in the Climate System

The Greenland Ice Sheet is the largest single contributor to rising global sea levels, and monitoring the ice sheet and its many outlet glaciers is at the forefront of several important NASA-funded research projects. King et al. (2020) combined more than three decades of remotely sensed observational products of outlet glacier velocity, elevation, and front position changes over the full ice sheet. They compared decadal variability in discharge and calving front position and found that increased glacier discharge was due almost entirely to the retreat of glacier fronts with a consistent speedup of 4–5% per kilometer of retreat across the ice sheet. Widespread retreat of Greenland’s outlet glaciers between 2000 and 2005 resulted in a step-increase in discharge and a switch to a new dynamic state of sustained mass loss that would persist even under a decline in surface melt.

Understanding the dynamics of glacier change at the ice-ocean interface and how these changes cause extended thinning of glaciers upstream from their termini is critical for quantifying mass loss from the Greenland Ice Sheet. Work by Felikson et al. (2020) found limits to the inland spread of thinning that initiates at glacier termini for 141 ocean-terminating outlet glaciers around the ice sheet. Inland diffusion of thinning is limited by steep reaches of bed topography that are referred to in the study as “knickpoints.” They showed that knickpoints exist beneath the majority of outlet glaciers but they are less steep in regions of gentle bed topography, giving glaciers settling in less steep bed topography the potential to contribute to ongoing and future mass loss from the Greenland Ice Sheet by allowing the expansion of thinning far into the ice sheet interior.

Surface melting events supplying water to the bed of the ice sheet and the subsequent subglacial processes that drive ice accelerations were documented by Smith et al. (2021), where the team examined linkages between surface runoff, transient subglacial water storage, and short-term ice motion from 168 consecutive hourly measurements of meltwater discharge (moulin input) and GPS-derived ice surface motion for a moulin-terminating supraglacial river catchment on the southwest Greenland Ice Sheet. They found that one important factor influencing the speed of a sliding glacier in southwest Greenland was how quickly water pressure changed within cavities at the base of the ice where meltwater met bedrock. The findings contradict a long-held view about ice sliding velocities and water stored under a glacier known as steady-state basal sliding law, which has helped scientists predict how fast ice sheets will slide based on the total volume of water underneath the ice.

Observations of subglacial processes happening at the base of the Antarctic Ice Sheet are becoming increasingly possible with the dense geographic coverage and seasonal repeat measurements from ICESat-2. Siegfried and Fricker (2021) demonstrated the ability to continue monitoring active subglacial lakes at timescales shorter than ICESat-2’s repeat cycle and generate time series of subglacial lake surface-height anomalies from combined ICESat, CryoSat-2, and ICESat-2 altimetry. Focusing on three regions with known significant lake activity, they showed that ICESat-2 laser altimetry can not only extend the record of subglacial lake activity but also provides better understanding of hydrological processes by capturing denser and more precise spatial detail.

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 over the globe. The continuous exchange of properties between the ocean and the atmosphere influence 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.

NASA's [Physical Oceanography Program](#) supports a wide range of studies that quantify the ocean's role in the climate system by utilizing remote and in situ observations, numerical models and data assimilating systems. The program supports research that characterizes both ocean's intrinsic variability, its dynamics and thermodynamics, as well as ocean's interactions within the complex ocean-atmosphere-land-solid Earth system. Below are the most notable discoveries in 2020-2021 that advanced our understanding of the ocean's role in the climate system.

Ocean dynamics as a regulator of Earth's heat budget

The oceans have an important role in the Earth's Energy Imbalance, a term referring to the difference between how much solar radiant energy is absorbed by Earth and how much thermal infrared radiation is emitted to space. Since most of the excess of this energy goes into the oceans as heat, effectively delaying the full consequences of global warming, ocean heating rates can be used to infer Earth's top-of-the-atmosphere net radiation. A new study by *Loeb et al. (2021)* uses NASA atmospheric and ocean observations along with in situ data to determine the heating of the oceans and top-of-the-atmosphere over the past decades. The two independent approaches demonstrate that there is a decadal increase in the rate of energy uptake by Earth from mid-2005 through mid-2019, consistent with observational estimates of warming of land and atmosphere as well melting of snow and ice. The marked increase in Earth's heating rate and ocean warming is attributed to decreased reflection of energy back into space by clouds and sea-ice and increases in well-mixed greenhouse gases and water vapor.

Ocean circulation redistributes and dissipates some of this extra energy so one region is not constantly heated. The western tropical Pacific Ocean Features complicated ocean circulation systems and has the warmest open-ocean waters. Here, even small upper-ocean temperature changes can exert significant impact on regional ecosystems, including corals. A new study by *Qiu et al. (2021)* found that multiple coral bleaching events near Palau since 1998 are linked to the time-varying ocean circulation, rather than being a passive response to the atmospheric heating in response to ENSO variability. *Qiu et al. (2021)* demonstrated the importance of advection in

damping and redistributing the anomalous surface heat flux forcing, ultimately controlling thermal conditions around Palau and impacting coral bleaching events.

Besides ocean currents, mesoscale eddies are another player in the redistribution of the heat across the ocean. A new study by *Müller and Melnichenko* (2020) examines the structure and variability of the meridional eddy heat transport in the North Atlantic over the past 25 years using satellite altimetry and temperature data, along with in situ measurements. Observations show an increase in the eddy heat transport on average by 0.6 TW/year, accelerating to 1.3 TW/year after 2005. The increasing trend may lead to a warming of the surface layer of the subpolar North Atlantic by about 0.5°C per decade. The observed trends and variations in the eddy heat transport provide a considerable contribution to the variability of the total ocean heat transport, suggesting a potentially important forcing mechanism in the ocean component of the Earth climate system.

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 rates of surface warming. There are several ocean processes through which mixing can occur. One of them are internal waves, or waves that occur at various depths within the ocean. A comprehensive review study by *Whalen et al.* (2020) trace the energy pathways from tides, winds, and geostrophic currents to internal wave mixing. New knowledge of the spatio-temporal variability of the forcing and the complex life cycle of internal waves, including generation, propagation and breaking into turbulence, will provide a link of internal wave-driven mixing with the global climate system.

Ocean thermodynamics drives local sea level rise

Rising seas are a well-documented and most disruptive consequence of warming climate (e.g., *IPCC*, 2013). Hazards related to sea level rise impact highly-populated coastal communities, ecosystems, and national and global economy, threatening America's trillion-dollar coastal property market and public infrastructure (e.g., *USGCRP*, 2018) and potentially exposing up to 300 millions of people to risks of sea level rise and coastal flooding by 2050 (e.g., *Kulp and Strauss*, 2019).

While the causes of the global-mean sea level rise are well understood, commonly attributed to the ocean's thermal expansion and added water from melted land ice complexes, understanding and predicting the regional and coastal changes in sea level remains a challenge. Local and coastal sea level change, where the information is needed the most for stakeholders and decision-makers, are often impacted by a number of additional processes that cancel out in the global-mean, including the changes in ocean thermodynamics. A study by *Dangendorf et al.* (2021) sheds light on causes of coastal sea level variability on inter-annual to decadal time scales dating back to the 1960s. The results find that ocean circulation is dominating the coastal sea-level budgets over the past six decades. It is the ocean's dynamical processes that explains 91% of coastal sea level variability, which are primarily remotely forced by perturbation in the open ocean and transferred to the coast through the action of

(coastally trapped) Kelvin and Rossby waves. The results reinforce the importance of ocean observing in understanding and near-term predictions of coastal sea level change, coastal planning, and adaptation efforts.

More evidence of ocean-induced sea level changes, and the importance of ocean observations, is demonstrated by *Hamlington et al. (2021)*. Results focused on two locations with large departures from the global average sea level in opposite directions, suppressed off the west of the United States and elevated in the western tropical Pacific, *Hamlington et al. (2021)* examines how the ocean's intrinsic processes and ocean-atmospheric coupling impact regional changes in sea level. They determine that despite approaching 30 years of satellite altimetry observing record, large internal ocean variability still obscures underlying long-term trend in both regions, while also finding that the anthropogenic-related sea-level signal will likely emerge in coming years. The results have important implications for impact and planning perspective: suppressed trends along the west coast of North America could lead to complacency in planning or the impression that future sea-level rise will be similarly suppressed despite evidence for an ongoing increase in sea level in this region (see earlier studies e.g., *Bromirski et al., 2011; Hamlington et al., 2016; Piecuch et al., 2019*). Thus continued observations of sea level variability and persistence of decadal trends is critical for determining potential future impacts, including extended periods of elevated flood risk.

On the opposite coast, the rising seas of the U.S. Atlantic seaboard have been termed a "hotspot" of 20th century sea level rise. Among the underlying mechanisms contributing to increasing sea level along the eastern coast of the US, variability in ocean circulation and large-scale ocean transports are often mentioned as prominent factors. New study by *Piecuch (2020)* links sea level variability to the weakening of the Florida Current, which acts as a vital limb of the Atlantic Meridional Overturning circulation. A century-long sea level and transport reconstruction by *Piecuch (2020)* indicates that the weakest Florida Current ocean transport in the last 100 years likely took place in the past two decades, corroborating the overall decline of the prominent Atlantic Meridional Overturning Circulation over the recent past. By virtue of basic geostrophy, this large-scale northward ocean transport imparts an eastward acceleration due to the Coriolis force that is counteracted by a pressure gradient (and sea level difference) across the Florida Straits. The weakening of this large-scale transport decreases eastward acceleration and deflection of water masses away from the eastern US, leading to more water piling up along the coast and rising sea levels (note that weakening of the Atlantic ocean transport is also linked to an increased number and severity of winter storms and heat waves in Europe).

Ocean's role in the Earth freshwater budget

Observational and modeling studies suggest that the Earth water cycle is undergoing significant changes over the past half century in response to the warming climate, manifested by the increased moisture content in the atmosphere, increased evaporation and higher frequency of heavy rain events. Being the largest source of freshwater and global moisture supplier, including the moisture that falls as land precipitation, oceans

are in the center of the changing water cycle story, including its pattern amplification and trends.

Being sensitive to the amount of evaporation, precipitation, and melt, ocean salinity has emerged as an important indicator of the oceanic water cycle and its changes. NASA continues to improve its measurements of satellite surface salinity, providing information on freshwater changes in various ocean regions, including extreme environments of the Arctic ocean (*Vazquez-Cuervo et al.*, 2021; *Fournier et al.*, 2020) and highly-variable coastal regions near river plumes (*Fournier and Lee*, 2021).

In particular, salinity plays a prominent role in high-latitude oceans dynamics, including subpolar North Atlantic. A study by *Tesdal and Haine* (2020) examines a long-standing feature of alternating decades between the warming/salinification and cooling/freshening in the subpolar North Atlantic and Nordic Seas. They found that the decline in freshwater content in the Nordis Seas comes mostly from a drop in sea-ice export from the Arctic Ocean. These findings contribute to a debate about the nature of inter-annual and longer variations in freshwater and heat budget in the subpolar North Atlantic, which plays a large role in the global climate as a major transport of heat and carbon.

A recent study by *Liu et al.* (2021) continues developing the salinity "rain-gauge" concept, illustrating the use of salinity as an indicator of the changing water and heat cycles. *Liu et al.* (2021) report that the large-scale moistening of the atmosphere in response to increasing greenhouse gases amplifies the existing patterns of precipitation minus evaporation. This, in turn, amplifies the spatial contrast in sea surface salinity, which consequently leads to accelerated ocean heat uptake. Through a series of CO₂ doubling experiments, *Liu et al.* (2021) examine this mechanism on multi-decadal timescales and suggest that the transient climate response would increase by approximately 0.4°C without this process. Favorable comparisons with historical salinity observations indicate that the anthropogenically-forced changes in salinity are already enhancing the rate of ocean heat uptake, emphasizing the role of salinity as an important constraint in Earth's heat and freshwater budgets.

Ocean's role in marine extremes and coastal hazards

The oceans play an important role in regulating or intensifying extreme weather events, like storms and hurricanes. In a warming climate, periods of above-average ocean temperatures, known as marine heatwaves, are being observed more frequently.

Scannell et al. (2020) examines the nature of marine heatwaves in the Gulf of Alaska, reporting fresher than normal near-surface waters in 2019-2020. The anomalous freshening served as a barrier layer, inhibiting mixing with a deeper, cooler water and thus enhancing surface warming. This warming was found of similar nature to the infamous "Blob" event in 2013-2016, that upended Pacific fishing industry and marine food chain. According to *Scannell et al.* (2020), even if the warmer surface water gradually mixes downward, the heat can persist long after the surface marine heatwave disappears, suggesting that the ocean can provide memory for long-lived ocean thermal extremes.

Extreme drought and wildfire conditions in California are partially attributed to marine heatwaves off the California coast. *Wei et al. (2021)* observed waters 6.5°C hotter than average. The marine heatwave resulted from a gradual warming under relaxed wind and coastally-trapped waves that originated far away in the equatorial Pacific. The ongoing greenhouse warming elevates the risk of heat extremes in the ocean and on land, and the importance of monitoring individual heatwave events helps understand their physical mechanisms and improve predictions.

Unlike the droughts of the west coast of the United States, marine extremes in the Gulf coast are attributed to intensified hurricanes. *Dzwonkowski et al. (2020)* observed a powerful ocean warming event in the coastal waters of the northern Gulf of Mexico. It formed as a result of a strong atmospheric heatwave, which mixed heat all the way to the bottom of the Gulf, due to the tropical storm that went through the area. The extreme ocean temperatures, at surface and depth, occurred prior to the landfall of Hurricane Michael during October of 2018, having a compounding effect on its subsequent strengthening to a category 5 storm at landfall. Monitoring such supercharging coastal heat events is critical information for forecasting landfall storm intensification, particularly as their frequency is anticipated to increase under expected climate change conditions.

Integrated Earth System and 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 Modeling System, which includes the GEOS modular Earth system model, the GEOS data assimilation system, the GEOS coupled chemistry/climate model, and the GEOS 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 focused on characterization of the behavior of the Earth system included:

Climate modeling advances

NASA GISS Model E is NASA's primary tool for investigation of multidecadal climate and Earth system variability and change, and is supported by the CVC FA.. Kelly et al. [2020] describe an update model to version 2.1. This version was used to make contributions to the Coupled Model Intercomparison Project, Phase 6 (CMIP6). This version includes numerous parameterization improvements to the atmospheric and ocean model components and updates in forcings. Model skill when compared to modern era climatologies is significantly higher than in previous versions, resulting from improvements in representations of modes of variability (such as the Madden-Julian Oscillation and other modes in the Pacific) and significant improvements in the simulation of the climate of the Southern Oceans, including sea ice. The effective climate sensitivity to $2 \times \text{CO}_2$ is slightly higher than previously at 2.7–3.1°C (depending on version) and is a result of lower CO_2 radiative forcing and stronger positive feedbacks.

Surface air temperature trends and extreme events are of global concern and they are related. It is important to understand the degree to which Earth system models can reproduce observations. Zeng et al. [2020] showed that the occurrence of record hot years over different latitudes from 1960 to 2019 are more strongly correlated with the observational annual mean temperature trends when they are normalized by internal variability. Compared with the raw trends, which show Arctic amplification, the normalized trends show a tropical amplification over land. Two hot spots with more frequent occurrence of record hot years were identified: northern hemisphere ocean (vs. land) and southern hemisphere tropical land (vs. mid- and high-latitude lands). Ensemble mean results from 32 Earth system models agree with observations better than individual models, but they do not reproduce observed large differences in correlations across latitudes between normalized trends and record-breaking events over land versus ocean. These results enable the quantification of record hot year occurrence through normalized warming trends and provide new metrics for model evaluation and improvement.

The Covid-19 pandemic resulted in restrictions of travel and other activities during 2020, which temporarily reduced emissions of CO_2 , other greenhouse gases and ozone and aerosol precursors. Jones et al. [2021] describe a large intercomparison of Earth system model simulations - named CovidMIP - that assessed the impact on climate of these emissions reductions. Twelve models performed multiple initial-condition ensembles to produce over 300 simulations spanning both initial condition and model structural uncertainty. Models generally exhibited reduced aerosol amounts and increases in surface shortwave radiation levels, but only small to undetectable impacts on near-surface temperature or rainfall during 2020-2024. Higher resolution, regional studies are needed to fully understand the impacts of Covid-19 related emissions reductions on climate.

Chemistry/climate modeling advances

To understand and predict the role of atmospheric chemistry and composition in the climate system, the Goddard Earth Observing System composition forecast (GEOS-CF) system was developed and is described in Keller et al. [2021]. GEOS-CF is a major addition to the GEOS modeling system, and is a high-resolution (0.25°) global

constituent prediction system from NASA's Global Modeling and Assimilation Office (GMAO). GEOS-CF expands on the GEOS weather and aerosol modeling system by integrating the Harvard University "GEOS-Chem" chemistry module to provide hindcasts and 5-day forecasts of atmospheric constituents including ozone (O₃), carbon monoxide (CO), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and fine particulate matter (PM_{2.5}). The GEOS-CF chemistry module is maintained identically to the standard GEOS-Chem model and therefore continuously benefits from the innovations provided by the GEOS-Chem community. Evaluation of GEOS-CF against satellite, ozonesonde and surface observations for years 2018–2019 show realistic simulated concentrations of O₃, NO₂, and CO. Comparisons against surface observations successfully represent of air pollutants in many regions of the world and during all seasons.

Ozone is a greenhouse gas and its concentration in the atmosphere is controlled by both chemical and dynamical processes. In the stratosphere, age of air is an important diagnostic for models of global atmospheric dynamics. Strahan et al. [2020] showed that total columns of the trace gases nitric acid (HNO₃) and hydrogen chloride (HCl) are sensitive to variations in the lower stratospheric age of air. Analyses of HNO₃ and HCl columns from the Network for the Detection of Atmospheric Composition Change, combined with the age of air from a simulation using the MERRA2 reanalysis show that the Southern Hemisphere lower stratosphere has become 1 month/decade younger relative to the Northern Hemisphere, largely driven by the Southern Hemisphere transport circulation. The analyses reveal multiyear anomalies with a 5- to 7-year period driven by interactions between the circulation and the quasi-biennial oscillation in tropical winds. This hitherto unrecognized variability is large relative to hemispheric transport trends and may bias ozone trend regressions.

Land and land/atmosphere coupling modeling advances

The value of assimilating vegetation observations into ESMs is under exploration by CVC-supported researchers. Rahman et al. [2020] report advances in quantifying the impact of assimilating phenology observations using a direct insertion (DI) method by constraining the modeled terrestrial carbon dynamics with synthetic observations of vegetation condition. Specifically, observations of leaf area index (LAI) were assimilated into the Noah-Multi Parameterization (Noah-MP) land surface model across the continental United States during a 5-year period. An observing system simulation experiment (OSSE) was developed to understand and quantify the model response to assimilating LAI information through DI when the input precipitation is strongly biased. This is particularly significant in data poor regions, like Africa and South Asia, where satellite and re-analysis products, known to be affected by significant biases, are the only available precipitation data to drive a land surface model. Results show a degradation in surface and rootzone soil moisture after assimilating LAI within Noah-MP, but an improvement in intercepted liquid water and evapotranspiration. In terms of carbon and energy variables, net ecosystem exchange, amount of carbon in shallow soil, and surface soil temperature are improved by the LAI DA, although canopy sensible heat is degraded. Overall, the assimilation of LAI has larger impact in terms of reduced systematic and

random errors over the Great Plains (cropland, shrubland, and grassland). Moreover, LAI DA shows a greater improvement when the input precipitation is affected by a positive (wet) bias than the opposite case, in which precipitation shows a dry bias.

Ocean/atmosphere coupled modeling advances

Quantifying variability in the ocean carbon sink remains problematic due to sparse observations and spatiotemporal variability in surface ocean pCO₂, but is an important focus for the CVC FA. Carroll et al. [2020] describe an updated and improved ECCO-Darwin global ocean biogeochemistry model that assimilates both physical and biogeochemical observations to address this challenge. The model consists of an adjoint-based ocean circulation estimate from the CVC-funded Estimating the Circulation and Climate of the Ocean (ECCO) consortium and an ecosystem model developed by the Massachusetts Institute of Technology Darwin Project. In addition to the data-constrained ECCO physics, a Green's function approach was used to optimize the biogeochemistry by adjusting initial conditions and six biogeochemical parameters. Over seasonal to multidecadal timescales (1995–2017), ECCO-Darwin exhibits broad-scale consistency with observed surface ocean pCO₂ and air-sea CO₂ flux reconstructions in most biomes, particularly in the subtropical and equatorial regions. The ECCO-Darwin data product provides a basis for identifying and predicting the consequences of natural and anthropogenic perturbations to the ocean carbon cycle, as well as the climate-related sensitivity of marine ecosystems.

Observing system for climate variability and change advances

Observations of atmospheric winds are a high priority goal for Climate and Earth system characterization, particularly for development of assimilation and initialization of weather and short-term climate forecasts. McCarty et al. [2021] describe a set of observing system simulation experiments (OSSEs) using the GMAO OSSE system to investigate the utility of a constellation of passive infrared spectrometers, strategically designed with the aim of deriving the three-dimensional retrievals of the horizontal wind via atmospheric motion vectors (AMVs) from instruments with the spectral resolution of an infrared sounder. Such an observing system may be an inexpensive means for measuring atmospheric wind fields. The instrument and constellation designs were performed in the context of the Midwave Infrared Sounding of Temperature and humidity in a Constellation for Winds (MISTiC Winds). The experimentation showed beneficial impacts on both the mass and wind fields, as based on analysis verification, forecast verification, and the assessment of the observations using the forecast sensitivity to observation impact (FSOI) metric. The FSOI metric illustrated two key points. First, the largest impacts were seen in the middle troposphere AMVs, which is a targeted capability of the constellation strategy. Second, the addition of errors showed that the assimilation system was unable to fully exploit the 4.3- μ m carbon dioxide absorption radiances.

Section 1.1.8.4 Earth Surface and Interior Focus Area

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. Below are highlights of ESI Focus Area funded research accomplishments that have matured over the past year and represent research that has been funded over the past several ROSES cycles. Referenced ESI publications are also archived on ESDpubs (https://esdpubs.nasa.gov/pubs_by_program - select Earth Surface & Interior Program).

The scope of NASA's Earth Surface and Interior focus area (ESI) falls largely under the 1.1.8 "characterizing the behavior of the Earth system" performance goal. This includes the observation, analysis, and interpretation of any Earth surface or interior property or process using satellite, airborne, or associated ground instruments, along with computational and other assessment tools. Publications under this category contribute to improving interpretations of primarily space-based and remote sensing observations, identifying and addressing noise and other error sources, as well as the ability to characterize features related to the Earth surface and interior, such as mineral mapping, identifying earthquake deformation and source properties, and determining the presence and drivers of fluctuations in gravity and/or the electromagnetic field.

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. 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. Many of these studies have advanced to support upcoming missions, such as seafloor and mineral mapping, and

others are related to how geodesy can be used to measure the effect of fault dynamics and anthropogenic deformation.

Hydrogeodesy

Advances of space geodesy over the past decade have enabled transformative research progress in the rapidly evolving field of hydrogeodesy. Space-based observations and advanced geodetic techniques (e.g., GRACE-FO, 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.

Loading or unloading due to watershed volume changes can be measured by GNSS, InSAR, and Gravimetry and can be used to derive the amount of terrestrial water storage (TWS) available. Yin et al., (2020) applied Gravity Recovery and Climate Experiment (GRACE) data combined with GPS and hydrologic loading models to two snow-dominated basins in the western United States to estimate the amount of vertical displacement related to changes in TWS. It was found that vertical displacement from ground-based GPS could successfully detect heavy precipitation during the 2010–2011 winter as well as the following drought in the Great Basin and Upper Colorado basins. This improved on the limited ability of the hydrologic model alone to detect vertical displacement from the drought. Both Xue et al.(2021) and Argus (2020) applied hydrological models to the Great Lakes region using GNSS and GRACE data to determine how the TWS in the region changed from the period of 2013 to 2019, when the water level of the Great Lakes rose 0.7-1.5 m. Argus (2020) identified measurable loading as a result of both the increased volume of the lakes and the viscous collapse of the former Laurentide ice sheet forebulge. With these subsidence rates they identified that hydrologic models overestimated calculations of changes in TWS in the region and determined that the TWS in the Great Lake watershed increased by 50 km³ from 2013 to 2019. Xue et al.(2021) assessed the relative contribution of each individual hydrological component to the total integrated hydrological load and found strong correlations between the measured regional hydrological loading and modeled loading displacements. In this model, soil moisture contributed 27-69% of the measured loading whereas lake loading only accounted for 10-25% with the residual attributed to snow loading.

Rapid variations in the water cycle can have far reaching effects and can even act as the driving mechanism for geohazards. This is demonstrated in two different locations by Hammond et al. (2021) and Hsu et al., (2021). In the area surrounding Long Valley Caldera, Hammond et al. (2021) used GRACE data and the standardized relative climate dryness to measure the location and timing of droughts and found a correlation with magmatic inflation, as measured by GPS, due to surface unloading. This inflation acted as the triggering mechanism for small- to moderate sized earthquakes up to 60 km away. Hsu et al.(2021) had similar findings in Taiwan, where there was a strong correlation

between the timing of peak levels in seismicity and annual water unloading (February to April). However, they found this correlation to apply more closely to deep earthquakes in eastern Taiwan and that shallow earthquakes in this region were anticorrelated with hydrological unloading.

Anthropogenic influences, such as ground water injection and extraction, can affect the TWS in the region to such a large degree that it can be remotely measured using InSAR, GNSS, and GRACE. Massoud et al. (2021) used all of these data types to determine TWS changes in Beqaa Plain, Lebanon from groundwater depletion from June 2002-April 2017. After combining satellite data with information from available hydrologic cycle models they identified a subsidence rate of roughly 1.10 cm/yr within the Zahle district as a result of groundwater depletion. This result is echoed by the significant drop in water level in local monitoring wells throughout the region. Murray et al. (2021) applied an elastic Green's functions to InSAR data to recover three-dimensional displacement fields in the Coachella Valley. They found ground displacements of up to 12 cm in 2017 from ground water recharge. Using their new methodology, they determined that the displacement was likely associated with significant horizontal displacements that led to contraction across the fault bounding the northern side of the basin, as well as increases in right-lateral sense of strain in some areas along the fault.

Anthropogenic Deformation

InSAR and GNSS have proven effective at measuring anthropogenic deformation. This can be caused by the added loading effects the mass of a city can have on a location, or how the Earth responds to subsurface fluids being extracted. Both Staniewicz (2020) and Kim et al., (2021) observed and measured deformation as the result of oil production in the Permian Basin. Staniewicz (2020) uses InSAR data from November 2014 to January 2019 to map deformation in response oil pumping and fluid injection over 80,000 km² in Texas using new techniques that allowed for ~2mm/yr accuracy. They found increased seismic events near Pecos, TX that correlated with the timing and location of linear deformation signatures related to horizontal drilling. Kim and Lu (2021) examined thousands of aging unplugged oil wells using InSAR and found that they have the potential to create ground instabilities and damage to the environment. These uncapped wells enable freshwater to leak through water-soluble soil layers, resulting in subsidence, collapse sinkholes, and ground fissures, with subsidence rates exceeding 50 cm/yr at some locations. This study demonstrates the importance of proper management and maintenance of these wells.

Seafloor Mapping

With the planned launch of NASA's Surface Water and Ocean Topography (SWOT) mission just over a year away, there has been an increased interest in mapping seafloor topography with existing techniques that can be applied and leveraged by SWOT. Herper et al., (2021) used Vertical Gravity Gradients (VGG) to identify "seesaw" ridge propagation. This type of propagation is significant because it can be used to map spreading rates and seafloor ages, they form on young and thin lithosphere, and do not

correlate with previous regional scale models of ridge propagation, thus requiring a different driving force. Zhang et al., 2021 used CryoSat-2, Jason 1/2, and SARA/Altika satellite altimetry to map the marine gravity field by using methods based on sea surface height (SSH) and sea surface slope (SSS). They found that SSH had greater accuracy in coastal zones and SSS had the advantage in regions with intermediate depths (2000-4000m) with seamounts and ridges, both methods performed similarly in the deep ocean and at areas with plain and smooth topography.

Mineral Mapping

Using image spectroscopy techniques, satellite sensors acquiring imagery in the VNIR, SWIR, and TIR wavelengths are able to determine surface compositions. The Earth Mineral dust source InvesTigation (EMIT) sensor is due to launch to the ISS in mid-2022 and will be used to map the surface mineralogy of Earth's dust source regions using spectroscopic analysis in order to determine the role they play in dust formation and radiative forcing. Connelly et al. (2021) developed a method to assess the impact of uncertain remote observation of Earth system models (ESMs) that will be used to make surface mineral determinations on EMIT. In doing so, they determined that EMIT data stand to significantly reduce uncertainty in estimates of the dust direct radiative forcing attributable to uncertainties in surface mineralogies that are input into ESMs. Farrand and Bhattacharya (2021) used Airborne Visible Infrared Imaging Spectrometer-Next Generation (AVIRIS-NG) data to track acid generating minerals that could contribute to acid mine drainage at abandoned and active mining sites in northwestern India. By searching for a 2.2 μm absorption features in the drainages from two mines, the Ambji and Zawar mining sites, they were able to successfully identify the spread of acid mine drainage to the surrounding environment. Kumar et al., (2021) developed three new Spectral Mapping Measures (SMM) algorithms named the Dice Spectral Similarity Coefficient (DSSC), the Kumar-Johnson Spectral Similarity Coefficient (KJSSC) and a hybrid of the two (KJDSSC), that allow for the accurate discrimination of spectrally similar materials and minerals. These SMMs outperform previous SMMs when discriminating noisy and linearly synthesized mixed counterparts, KJSSC and DSSC can efficiently discriminate the spectra of minerals and vegetation whereas the hybrid, KJDSSC, shows significantly higher spectral discrimination ability. They propose that this hybrid algorithm is more effective and should replace existing SMMs for material discrimination and classification using hyperspectral data.

Fault Dynamics

Lithospheric fault dynamics can govern the frequency, depth, and location of earthquakes. By developing methods to better understand and map these dynamics, researchers can recognize one the drivers for the behavior of earthquake events. Lou and Liu (Nature, 2021) examined fault zone heterogeneities to explain depth-dependent patterns and the evolution of slow-slip earthquakes in Cascadia. They found that these earthquakes display diverse behavior at different spatiotemporal scales and had an increase in frequency with depth. A model was developed to reproduce the full complexity of observed episodic tremor and slow-slip patterns that agreed quantitatively

well with observations as well as the observed depth-frequency scaling. This suggests that fault zone heterogeneities can be one viable mechanism to explain a broad spectrum of transient fault behaviors. Liu et al. (2021) examined the rheological structure model of a strong crust that overlays a low-viscosity mantle asthenosphere that has been favored in the Eastern California shear zone and found this model needed to be revised based on the timing of the post-seismic events of two earthquakes in this region. They proposed a “thin crème brûlée” model where both the lower crust and the upper mantle exhibit ductility at decadal time scales. Li and Bürgmann (2020) studied the Xianshuihe Fault which is a shallow creeping fault that has been associated with substantial seismic potential, with more than 20 $M_w > 6$ earthquakes since 1700. InSAR data were used to determine the spatial and temporal distribution of this fault resulting in the identification of multiple creeping sections and estimated surface creep rates with high along-strike variability, providing constraints on the locked and creeping sections of the fault.

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. Recent studies have focused on the afterslip period of earthquakes, fully utilizing NASA instrumentation to detect volcanic activity, and slow-moving landslides. 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

During a seismic event, both the initial rupture and afterslips pose significant risk, therefore both need to be analyzed and understood. Milliner et al., (2020) studied the first hour following the 2016 Kumamoto earthquake using InSAR, GPS, and pixel offset geodetic data. They found that early (within the first hour) after slip movement contributes to ~ 1% of the total moment release and 8% after 24 hours, there is no evidence of a delayed nucleation or acceleration phases, and that there is a close correlation between near-field after shock and afterslip within the first hours following the rupture. Wang and Bürgmann also studied the fault frictional properties of postseismic afterslip updip and downdip of the 2017 Sarpol-e Zahab earthquake using InSAR data. They found the updip and downdip movements to be explained by oblique afterslip of the coseismic peak area and that the fault angle of afterslips were significantly smaller than that of the coseismic rupture.

Glacial Isostatic Adjustment (GIA) caused by the mantle responding to the removal of loading from the melting of glaciers can also lead to seismic activity. Rollins et al. (2021) calculated the impact both GIA and inter-earthquake stress transfer had in the occurrence of earthquakes in southern Alaska. They found that GIA promoted stress led to failure along the St. Elias compressional of earthquakes in southeast Alaska and they estimated

that 23 of 30 instrumentally constrained $M_w \geq 5.0$ earthquakes in this region were also promoted by post-1770 GIA.

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 fewer are monitored consistently. Thus, current and future Earth-observing satellite missions, with global and frequent measurements of volcanic activity, are critical. Reath et al. (2021) developed the first archive of both satellite and ground-based seismic, deformation, degassing, and thermal data to quantify the amount of detectable volcanic activity in the United States and its territories. This study found 96 volcanoes in the US with some type of volcanic activity, with newly identified thermal activity at 30 volcanoes from analysis by the ASTER sensor. Flower and Kahn (2020) used MISR, MODIS, and OMI to classify and track volcanic emissions from Icelandic volcanoes based on content and ash particle size. They used these data to illustrate the potential to distinguish qualitative differences in eruptive magma composition based on particle light absorption and plume profile from remote sensing. Gonzalez-Santana and Wauthier (2021) examined the long-term flank instability at Pacaya volcano using InSAR data from 2010 to 2014. This study highlights that long-term volcanic flank creep is likely more widespread than previously recognized and that magma-faulting interactions, as well as the existence of structural weaknesses within volcanic edifices, are vital considerations in the assessment of likelihood and nature of flank collapse at volcanoes worldwide.

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. The effect these mechanisms have during the landslide event can be directly observed in slow-moving landslides. Bekaert et al. (2020) applied novel InSAR techniques in the steep and mountainous terrain of Nepal to determine methods for mapping and monitoring slow-moving landslides. They identified 6 slow-moving landslides in the study area and highlighted the potential for region-wide mapping of slow-moving landslides using remote sensing data in remote areas around the world. Dille et al. (2021) used InSAR and optical pixel tracking to provide an analysis of the dynamics of a slow-moving landslide in a tropical environment. They determined that rainfall-induced changes in pore-pressure acted as the main control on landslide motion, however other mechanisms, such as nearby earthquakes and internal landslide kinematics, are needed to fully explain its behavior. They also demonstrated how high-resolution optical data that can be captured below the cloud layer by UAS can be critical in identifying the complex kinematic patterns of landslides.

Lu and Kim (2021) developed a framework for studying hydrology-driven landslide hazards by applying InSAR data to the northwestern US, which is prone to heavy rainfall and is subject to hundreds of landslides per year. InSAR time-series displacements were

used to provide an indication of landslide occurrence and extent and help characterize basal slip surface and slide-body volume. These parameters are tracked through correlation and slope stability analysis to understand landslide dynamics. The authors demonstrated how satellite observations of landslide motions and the attributing hydrological variables from both radar and optical images improve our understanding of the inter-relationships between the hydrologic processes and landslide kinematics and mechanisms on a regional scale.

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. Global-scale research on the Earth's interior utilizes gravity, topography, magnetic, or other geodetic methods and associated modeling and analysis to advance and require 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].

Magnetic Field

Polar motion on decadal time scales has long been believed to be influenced by equatorial angular momentum between the solid Earth mantle and fluid outer core through the mechanism of electromagnetic (EM) core mantle coupling. Alken et al.(2021) adopted the thirteenth generation of the International Geomagnetic Reference Frame (IGRF), a set of spherical harmonic coefficients which can be input into a mathematical model in order to describe the large-scale, time-varying portion of Earth's internal magnetic field between epochs 1900 A.D. and the present. The new IGRF updates the previous generation by including a definitive main field model for epoch 2015.0 and 2020.0 as well as predictive linear secular variation for 2020.0 to 2025.0. This secular variation model is described further in Tangborn et al. (2021), where it is discussed how they developed a predictive model for the 2020-2025 time period by estimating mean secular variation of the geomagnetic field using the NASA Geomagnetic Ensemble Modeling System (GEMS).

Mass Loading

Deformation of the surface is indicative of subsurface movement that can at times be related to a deep Earth shift of mass within the mantle. These shifts can occur as a result of changes in mass loading on the surface, either from the removal of mass (e.g., glacial melting) or from the addition of mass (e.g., building of urban locations). The manner in which these shifts occur can be used to calculate the properties of the mantle. Argus et al. (2021) used GPS, GPS, GRACE, and Relative Sea Level Measurements of GIA to

determine the viscosity of the top third of the lower mantle based on the measured uplift. They found uplift at the ice center to be about 12 mm/yr, supporting the low value of the viscosity of the top 500 km of the lower mantle of 1.6×10^{21} Pa s (from ICE-6G_D (VM5a)), but ruling out the high value of 13×10^{21} Pa s (from L17). Gualandi and Lie (2021) applied InSAR to the San Joaquin Valley and the Central San Andreas fault (CSAF) from 3/15 to 7/19 to isolate the multitude of contributions that lead to surface deformation. They applied a variational Bayesian independent component analysis (vbICA) algorithm and were able to isolate the contribution of shallow and deep aquifers to the surface deformation as well as the elastic and inelastic deformation. The application of this algorithm helped to separate tectonic loading from seasonal behavior concentrated in the Quaternary sediments of the Salinas Valley. Martens and Simons (2021) made a comparison of predicted and GPS observed ocean tidal loading (OTL) over 5 years in Alaska. They found that discrepancies between predicted and observed OTL displacements can be significantly reduced by removing a network-uniform tidal-harmonic displacement, and that the remaining discrepancies exhibit some regional-scale spatial coherence, particularly for the M2 harmonic and suggest that the remaining tidal discrepancies cannot be fully explained by measurement error and instead convey information about deficiencies in ocean-tide models and deviations from spherically symmetric Earth structure.

Tectonics

Tectonics influence large regions of the Earth and can provide insight into the deep Earth as well as help to explain the occurrence of orogenic and earthquake events. Broermann et al. (2021) applied GPS velocity field measurements to deformation occurring in the southern Basin and Range and Colorado Plateau regions to calculate extensional strain rates. They found the highest strain rates in southern Arizona and suggest it may represent the potential for one or more rare, future, large-magnitude earthquakes, despite the lack of quaternary faults in the area, or indicate strain is being released through other processes. Lau et al. (2020) studied the vertical velocity field of the contiguous United States (CONUS) using GPS data from 2007 to 2017. They developed a new vertical crustal velocity field with consistent treatment of time series outliers, noise, and offsets, and adaptive smoothing and interpolation to account for spatially varying station density. This velocity field reveals spatially coherent vertical features that are representative of regional tectonics, hydrologic, and anthropogenic processes and by removing these effects from GRACE data they demonstrate residuals potentially due to geocenter motion and underlying tectonics.

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) Science Team

The Earth Science Technology Office funded a prototype “smart-tasking” tool under PI Cathleen Jones with the idea to demonstrate that a web-based interface to accept urgent response request from registered users could facilitate the collection, disposition, and forwarding of requests to the NISAR mission operations team, thereby aiding in disaster relief and mitigation during operations by systematically handling more and varied urgent response scenarios. Upon successful demonstration, the NISAR mission operations team adopted the tool for implementation, recognizing that it would streamline their operations. The tool automatically polls early warning services like the USGS PAGER (Prompt Assessment of Global Earthquakes for Response) system, discovers the location of events that meet the preset threshold of severity, and issues a request to mission operations in a predefined format.

Members of the NISAR science team, led by David Bekaert at JPL, also conducted a study of tropospheric models that could be used for operational production of differential path delay corrections to interferograms. This approach seeks to mitigate the effects of atmospheric water vapor as a noise source in the geodetic time-series thereby increasing NISAR’s ability to resolve and track land/ice surface movement. The team was joined by community members around the world with interest in atmospheric modeling and quality analysis. The team considered a number of models, then selected the ECMWF HRES, ERA5, NCUM, GEOS models for detailed evaluation. The criteria for selection were accuracy relative to global GNSS station estimates of path delay, resolution, latency, and availability. The team selected the ECMWF HRES model.

The NISAR science team established an IDEA committee led by Susan Owen at JPL to establish a sustainable, targeted, and meaningful narrative and action plan for diversity and inclusion in the context of a NASA mission. The initial meetings have been to establish the charter of the group, its scope, and near-term actions. It is recognized by the group that the project is ephemeral relative to the sustained effort needed to affect change, but the team believes that an effective framework validated by actions and results in the project context can provide a lasting impact.

The NISAR Project conducted a workshop on Earthquake Hazards and Induced Seismicity. The workshop was organized jointly by NASA and USGS and focused on advancing the use of data acquired by NISAR within the community of end users responsible for earthquake hazard monitoring and emergency response. The main objective of the workshop was to identify the highest priorities of the end-user community that would facilitate their ability to use NISAR data to improve operations. The meeting was held virtually on Sept. 17-18, 2020, in two half-day sessions. The workshop brought together participants from local, state and federal agencies, academia, NASA headquarters and the NISAR Science Team to discuss end users’ needs within the context of the mission capabilities, provide input on high value end user information

needs that can be addressed with radar remote sensing, and generate a roadmap for joint activities that will improve the utility and utilization of NISAR data when they become available. The outcomes were documented in a workshop report available on the NISAR website.

Following on the success of the 2020 UNAVCO virtual training for geodetic imaging, members of the NISAR project science and algorithm development team will repeat the training in August 2021. This year, 150 students have been selected out of a pool of nearly 450 applications. Once again, the training will last 5 days, and use processing scripts and algorithms that will support NISAR geodetic processing on the cloud. The cloud-based processing system is the Alaska SAR Facility's OpenSARLab. ASF is the NISAR DAAC.

The Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) Facility

During the time period from July 1, 2020 to June 30, 2021, UAVSAR conducted 61 science/engineering flights totaling 290 flight hours despite the pandemic shutdown that impacted/delayed several campaigns. Between the L- and P-band radars, we acquired 560 flight lines over the United States, participating in 2 major campaigns including the SnowEx campaign in the Rockies and the Sierra Nevada and the EVS-3 Delta-X campaign in Mississippi Delta, as well as several solid Earth DInSAR studies including the San Andreas Fault monitoring, the California landslides, and the Pacific deep-seated landslides. UAVSAR also acquired data for an oil slick study and wildfire response efforts. The project supported 14 Principal Investigators and 2 science teams performing research in 5 science disciplines, as well as rapid response efforts and technology development.

UAVSAR team also led the accommodation of Indian Space Research Organization's (ISRO) airborne L/S-band SAR (ASAR) aboard NASA's Gulfstream jet to conduct science campaigns in the US to prepare the science community for the NISAR mission. The phase 2 ASAR campaign (July 2021) collected data over the Great Lakes, Southeast and Northeast US to support research on wetlands, glaciers, oil slick mapping, soil moisture estimation, and instrument calibration/validation. The phase 3 campaign in the second half of July 2021 repeated much of the phase 1 observation of sites in Alaska and the Pacific Northwest including geological mapping of major volcanoes in Washington and Oregon and glacial/permafrost/sea ice studies in Alaska. The ASAR team also collected data over the Dixie Fire north of Sacramento. Results will support the development and evaluation of algorithms for the NISAR mission, planned to launch in 2023. In all, the ASAR project conducted 17 science/engineering flights totaling 83 flight hours and acquired 144 flight lines for 14 Principal Investigators supporting 10 science disciplines.

Highlights of this year's UAVSAR science campaigns included San Andreas fault monitoring and California landslides mapping. L-band observations acquired over the San Andreas since 2009 are being used to generate DInSAR products and estimate Line of Sight velocity. Results reveal shallow fault slip and locking distribution and help

quantify along strike surface fault creep variation. Handwerger et al. (EOS, 2021) collected UAVSAR data over 134 slow-moving landslides in the northern California coast ranges to calculate 3-D velocity measurements of landslide size as well as to infer the actively deforming thickness, volume, geometric scaling, and frictional strength of each landslide. They found that the largest landslide complexes in our data set become large primarily by increasing in area rather than thickness and that the slow-moving landslides display scale-dependent frictional strength. This suggests that large landslides tend to be weaker than small landslides, mostly due to larger landslides having a larger composition of weak material. They demonstrate how UAVSAR techniques can be used to better understand landslide processes and quantify their contribution to landscape evolution and hazards to human safety.

The UAVSAR system is over a decade old and so it has been necessary to begin working on modernizing the radar system to maintain current capabilities with an eye towards developing the next generation airborne SAR platform. The NextGen Airborne SAR virtual workshop was held during June 2020 with a subsequent report delivered to NASA HQ. Using feedback from the science and applications communities, they developed a preliminary UAVSAR-NextGen implementation plan, including porting of the radar to the G-V platform to allow for longer range observations as well as simultaneous dual-frequency operations and developing a new digital electronics backbone of the NextGen development in support of STV incubation and SDC concept studies. The UAVSAR team is evaluating prototype L-band transmit/receive modules (TRM) that will replace current TRMs that have failed.

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 time series of surface deformation applicable to many scientific and applied studies. Atmospheric, vegetation, and anthropogenic derived 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.

Jiang and Lohman (2021) applied coherence-guided InSAR deformation analysis to determine how factors such as vegetation changes from agriculture and soil moisture variability, may impact InSAR time series and to resolve time-varying deformation due to tectonic processes and geothermal energy production. They explored the Imperial Valley from 2015 to 2019 and examined the temporal variability of InSAR data via interferometric phase coherence to better distinguish signals and noise associated with agricultural activities, shoreline changes, or surface soil conditions. They observed a diverse suite of natural signals over multiple spatial scales, including steady interseismic deformation, seasonal lake-level-modulated signals at the southeastern Salton Sea shore, and transient slow slip on the Superstition Hills fault. This demonstrated the need to assess whether InSAR signals result from surficial changes or deeper sources. Stephens et al. (2021) focused on correcting tropospheric artifacts in InSAR data over two Nicaraguan volcanoes using Global Weather Models (GWMs). These GWMs were found

to be very case-dependent, based on the temporal resolution of the model and, at the volcanoes studied, none of the GWMs were able to accurately capture the tropospheric phase delays. Sun et al., (2020) applied an end-to-end convolutional neural network (CNN) with an encoder-decoder architecture to automate InSAR data processing and denoising to separate volcanic signals from atmospheric signals and noise. This approach was found to efficiently suppress atmospheric and other noise to reveal the noise-free surface deformation from unwrapped surface displacement maps with variant signal to noise ratios (SNRs).

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.

NASA Space Geodesy Network

All NASA VLBI and SLR stations continued to operate during the COVID-19 pandemic, maintaining or exceeded levels of scientific data output achieved in prior non-pandemic years. In 2020 the NASA SLR network tracked 54,474 satellite passes while the new NASA VLBI Global Observing System (VGOS) network had 45 sessions and the legacy VLBI network had 179 sessions. A new high-speed data circuit enabling e-transfer of VLBI data from the Hawaii stations to analysis centers was implemented that eliminates the need to physically ship disk packs.

The 7 NASA SLR stations continued to track around 120 satellites, including Sentinel-6 Michael Freilich/Jason CS that was launched Nov 21, 2020. The NASA SLR network also supported a special campaign of tracking the Galileo satellites for the Galileo Survey of Transient Objects Network (Gaston) Project (organized by the Paris and Cote d'Azur Observatories and the Royal Observatory of Belgium) to search for evidence of Dark Matter (DM) in the universe. SLR tracking of ICESat-2 and GRACE FO helped determine the radial accuracy of the orbits determined by GNSS (e.g., Thomas et al., 2021).

SGP continued to advance VGOS by operating its broadband VLBI stations at Kōke'e Park Geophysical Observatory (KPGO) in Hawaii, Goddard Geophysical and Astronomical Observatory (GGAO) in Maryland, McDonald Geodetic Observatory (MGO) in Texas, and Westford in Massachusetts. The 2-station next-generation VLBI UT1 (Universal Time) "Intensives" program between KPGO and Wettzell, Germany, that measures the variation in the rotation rate of the Earth expanded to twice a week and demonstrated equivalent or better performance than legacy VLBI Intensives. These

sessions augment the legacy VLBI Intensive series and are used by the IERS Rapid Service/Prediction Center at the U.S. Naval Observatory for the determination and prediction of the time-varying alignment of the Earth's terrestrial reference frame with respect to the celestial reference frame (i.e., Earth Orientation Parameters). Niell et al. (2021) measured the components of the 31-m-long vector between the legacy and next-generation VLBI stations at KPGO independently verifying the standard optical survey values obtained by the National Geodetic Survey (NGS). The expanded VGOS sessions and local tie measurements at KPGO are being used operationally for the first time for the realization of the 2020 International Terrestrial Reference Frame (ITRF2020).

The development of the next-generation SLR systems for Texas, Maryland, and Svalbard advanced despite challenges from the pandemic. All three telescope gimbals were built; the first one was successfully integrated with its telescope. Several other subsystems for the first system were also completed, including the Time & Frequency Subsystem and the Laser Hazard Reduction System Radar.

Petrov (2021) developed a wide-field very long baseline array (VLBA) calibrator survey from 13,645 VLBI radio source observations, creating the largest VLBI catalog ever published. This enabled the use of input catalogs with low position accuracy and the detection of a compact component in extended sources. Also, unlike previous absolute astrometry campaigns, both steep- and flat-spectrum sources were observed. Popkov et al., (2021) used VLBA to survey a complete north polar cap sample of 482 radio sources. They found 72% of these sources to have a steep single-dish spectrum and a detectable parsec-scale structure. The fraction of sources with a detectable parsec-scale structure is above 95% among the flat-spectrum objects and close to 25% among the steep-spectrum objects. These results show that future VLBI surveys aimed at searching for new sources with parsec-scale structure should include not only flat-spectrum sources but also steep-spectrum ones to have a more robust representation.

Terrestrial Reference Frame Combination

Efforts this past year have centered on developing and validating the Square-root REference Frame filter (SREF) analysis software that will be used to generate JTRF2020, the NASA/JPL candidate solution for ITRF2020. The NASA/JPL approach to the Terrestrial Reference Frame (TRF) is fundamentally different from the traditional approach. Rather than models of station motion, JTRF is a set of time series of smoothed, actual observed station positions. An advantage of this approach is that station positions and predictions can be updated using the latest geodetic observations rather than having to update the TRF model by reanalyzing all the data, as is currently done with the current International Terrestrial Reference Frame (ITRF) every 5 – 6 years. NASA/JPL will develop a TRF solution using the time series approach and submit it for consideration as a candidate to become the next ITRF.

The NASA/GSFC VLBI analysis center coordinated the contribution of the VLBI technique to the next realization of the ITRF, (ITRF2020), using data from 1979-2020. The VLBI submission implemented a new high-frequency EOP model, antenna gravity

deformations, atmospheric pressure loading at VLBI stations, and a priori estimate of galactic aberration. This is also the first time that VGOS data were included in the submission. The operational VGOS network has grown in the last year to about nine stations internationally, four of which are operated by the SGP.

The SGP supported University of Maryland/Joint Center for Earth Systems Technology also coordinated the SLR contribution to ITRF2020 using SLR observations to the LAGEOS, LAGEOS-2, and Etalon satellites from 1983 to 2021.

The NASA/GSFC DORIS analysis center contributed to ITRF2020 by reprocessing 27 years of data from 1993 to 2021 for 12 scientific satellites tracked by DORIS, including Jason-3. The DORIS submission implemented a new high-frequency EOP model, new gravity model based on more data from the GRACE & GOCE missions, improved modeling of non-conservative forces for different satellites, new phase law for Alcatel antennae from CNES, and applied elevation-dependent weighting.

Wu et al. (2020) cross validated GRACE data with GNSS geodetic displacements for complete and continuous monitoring of surface water mass variations to improve global nonlinear surface mass variation estimates. With this method, more robust geocenter motion results are achieved than previous GNSS alone estimates. They demonstrate significantly improved GNSS data after reprocessing and the refined Estimating the Circulation and Climate of the Ocean (ECCO) bottom pressure model revealed a global surface mass variation pattern that has been largely reconciled with that from GRACE data.

Global GNSS Network

The NASA Global GNSS Network (GGN) remains a state-of-the-art scientific GNSS network, providing high quality, multi-GNSS measurements to NASA and researchers throughout the world through participation with the International GNSS Service (IGS). Operations and maintenance were successfully conducted during the COVID-19 Pandemic while adhering to all relevant safety procedures.

An important contribution to NASA Earth Science from the GGN has been the operations and maintenance of a GNSS station supporting the altimetry calibration facility at the Harvest Oil Platform (off Point Arguello by Vandenberg AFB). Beginning with TOPEX/POSEIDON, the GGN and NASA partners have leveraged infrastructure provided by the Platform whose intended function was for the production of crude oil. The Platform is to be mothballed for oil production and the GGN is working with other NASA elements to extend continued scientific operations on the Platform and thereby provide continuity for current altimetry mission transitions.

JPL Geodetic Analysis Center

The JPL Geodetic Analysis Center has made progress on all fronts while still successfully producing and delivering a full suite of GPS analysis products and sustaining GipsyX

Geodetic Data Analysis software for NASA and other researchers. Standard operations and progress on new development were made in spite of the COVID-19, with personnel working from home.

A major effort was devoted this last year reprocessing GPS data for contributions to the development of the next ITRF, ITRF2020. This reprocessing requires analysis of GPS measurements going back to the early 1990s. Reprocessing of GPS is complete, and the results have been provided to the International GNSS Service.

Progress in transition from GPS-only to multi-GNSS operations was made. Effort has been focused on Galileo since it has been shown that the combination of GPS + Galileo produces significant benefit over GPS alone. Efforts for the remainder of this year will be centered on further developing operations software and procedures to add reliable, regular production of GPS + Galileo products to the suite of products available to GipsyX users and the IGS.

Development of multi-technique capabilities also continued. Integrating SLR and VLBI capabilities with existing GPS analysis capabilities to analyze data from large multi-technique networks has begun and technical issues are being worked. The capability to analyze data from multi-technique networks will ultimately support a major research effort in advanced methods for establishing terrestrial reference frame solutions, co-sponsored by NASA and the National Geospatial-Intelligence Agency (NGA).

SGP International and Interagency Cooperation

SGP continues to be a key participant in the United Nations Committee of Experts on Global Geospatial Information Management's Subcommittee on Geodesy. UN efforts to establish a UN GGIM Global Geodetic Centre of Excellence have advanced in the past year, with an initial offer by Germany to host the Centre at the UN Campus in Bonn, and supported by a public GGIM [Global Geodesy Forum](#). If successfully implemented, the Centre of Excellence could provide funded staff for advocacy and assistance for nations to invest in geodetic infrastructure and capacity development. Through SGP's representation on all of the Subcommittee's Working Groups (Governance; Geodetic Infrastructure; Policies, Standards and Conventions; Education, Training and Capacity Building; and [Communication](#) and Outreach), SGP is ensuring that the Centre is complimentary to, and not competing with, the International Association of Geodesy. SGP also participates in the UN [International Committee on GNSS](#) through the International Association of Geodesy (IAG) and International GNSS Service (IGS).

The IGS Central Bureau, based at JPL, completed the transition to a new IGS Website (www.igs.org). The new IGS Website includes user interface improvements in graphics, navigation, and updated IT security. The Website also allows IGS Working Group leaders to securely modify and update their group's presence on the IGS website with minimal intervention/assistance from the Central Bureau. The IGS Central Bureau also made strides toward more inclusive community engagement through improved social media engagement ([twitter](#), [LinkedIn](#), and [YouTube](#)), a quarterly [newsletter](#), and

celebrating our diversity of people and applications through [International Women's Day](#) and [International Day of Human Space Flight](#) communications campaigns.

The IGS Central Bureau also worked with members of the IGS Governing Board to complete work on the updated IGS Strategic Plan outlining Goals and Objectives for a sustainable, resilient, and innovative IGS moving forward; with plans for streamlined and integrated tracking of progress towards goals and objectives across IGS components.

Finally, the IGS Central Bureau worked closely with the IGS Governing Board to ensure the IGS continued successful operations during the COVID-19 pandemic. For example, the Central Bureau provided coordination and other support for remote IGS Governing Board meetings. Other events, usually taking the form of in-person meetings and workshops, were conducted virtually and scheduled in smaller sessions to accommodate the various schedules and time zones of the international Governing Board's membership.

SGP Contributions to Broad Science Mission Directorate Objectives

In order to collect accurate laser altimetry data, Precision Orbit Determination (POD) of the radial orbit to within 3 cm of real positions are needed. Thomas et al. (2021) calculated the POD of ICESat-2 by the reduction of Global Positioning System (GPS) double-difference carrier phase observable residuals with NASA Goddard Space Flight Center's GEODYN software. Independent SLR measurements are then used to verify the precision of POD performance. The residual analysis indicated that POD solutions have achieved a radial orbit accuracy just below 1.5 cm, thus exceeding the mission radial orbit accuracy requirement by more than a factor of 2.

The International Celestial Reference Frame (ICRF) is defined by the measured positions of extragalactic sources using VLBI relative to the barycenter of the solar system. This standard reference frame is used to define the position and orientation of planetary bodies, including Earth, as well as other astronomical objects and is needed to provide reference direction for satellite orbits, both of these measurements are critical to geodesy. Charlot et al. (2020) developed the third realization of the ICRF from 4536 VLBI sources measured over 40 years and integrated for the first time, the effect of the galactocentric acceleration of the solar system. This reference frame has increased accuracy, particularly at the traditional 8.4 GHz frequency, where a subset of 500 sources is found to have extremely accurate positions in the range of 0.03–0.06 mas. This third realization of the ICRF was adopted by the IAU at its 30th General Assembly in August 2018 and replaced the previous realization, ICRF2, on January 1, 2019.

Section 1.1.8.5 Water and Energy Cycle Focus Area

Introduction

Research funded by NASA's Water and Energy cycle focus area (WEC) seeks to improve our fundamental understanding of the water and energy cycles by developing tools and techniques that expand our abilities to: 1) detect, measure, track, model, and forecast global water storage and dynamics, 2) quantify how energy is transferred from the tropics to higher latitudes, and 3) 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 society's 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) 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 (i.e. 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 a limited budget profile. Below are highlights of WEC Focus Area funded research accomplishments that have matured in FY2021 and represent the research that has been funded over the past several ROSES cycles.

The scope of NASA's Water and Energy Cycle (WEC) focus area includes both the 1.1.8 "characterizing the behavior of the Earth system" performance goal, and the 1.1.9 "improve predictive capability" performance goal. WEC activities supporting performance goal 1.1.8 include observation, analysis, and interpretation of water and energy cycle fluxes and states using satellite, airborne, and in-situ instruments, along with computational and other assessment tools. Publications under this category contribute to understanding and improving the capabilities of observations, such as retrievals of states and fluxes, characterizing and quantifying error sources and uncertainties, as well as characterizing and measuring the quality of surface. Section 1.1.8 begins with four cross-cutting publications in the 'Water Budget and Water Cycle Dynamics' section that highlight climatic influences to water storage followed by subsections that showcase WEC's research in snow, surface water, High Mountain Asia, soil moisture, and groundwater. The second section of 1.1.8 titled 'Water – Ecosystem / Evapotranspiration

/ Drought / Wildlife / Water Quality’ describes new water related research that spans the hydrosphere and ecosphere.

Water Budget and Water Cycle Dynamics

The bulk of WEC research activities focus on the characterization, quantification, and modeling of the different elements of the terrestrial water cycle: precipitation, snow, surface water, soil moisture, biological/ecosystem water, and groundwater. These activities include advancing science from our current missions (i.e. SMAP, GPM, MODIS, GRACE-FO, ECOSTRESS, Landsat) and new research supporting missions that 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 publications that highlight climatic influences to water storage followed by subsections: Snow, Surface Water, High Mountain Asia, Soil Moisture, and Groundwater.

Knowing how much water is available is a universal need and a microcosm of this can be seen in the Himalayas and other mountains of central Asia, known as “High Mountain Asia.” It’s a place where hundreds of millions of people’s water supply depends on meltwater flowing down from high peaks. The snow and glacier ice where that meltwater originates are very sensitive to climate change, and a major research question is how will the water supply change in the future? Azam *et al.*, 2021 ([Science](#)), a review paper, summarizes much of the available research regarding this question, and also identifies key research gaps that need to be filled. Due to the difficult access to these mountain peaks, these key knowledge gaps span almost every aspect of the snow/ice patterns, including the need for improved inventories of the number, size, and thickness of the glaciers, and information on what a thawing permafrost would mean for the water supplies here. The High Mountain Asia region does contain weather stations, but most are located near villages nestled in valleys, which means weather data is missing from more treacherous mountain peaks. Many recommendations for pursuing some of these knowledge gaps are suggested, such as using GRACE data to study mass change in permafrost, and using Frequent Ground Penetrating Radar to create maps of the distribution of snow accumulation. Additional research in High Mountain Asia is presented in a dedicated section below.

One knowledge gap in particular is the effect of black carbon and dust on the snow and ice of these mountains. Black carbon, dust, and other airborne particles are widespread and can travel long distances from the polluted cities where they originate to the mountains. As these particles settle on and coat the mountainsides, they reduce the reflective properties of the snow and ice. In addition, these dark-colored particles are also adept at absorbing light. Both these factors mean that black carbon and dust can increase the speed of melting snow and ice, and even cause the snow and ice to melt earlier in the

spring. Sarangi *et al.*, 2020 ([Nature Climate Change](#)) looked at this issue in more detail. They used both CALIPSO overpasses and the MODIS Dust Radiative Forcing in Snow product to locate at which elevations the aerosols and dust layers were most prominent (between two and five km of elevation, peaking at five km). This information can be used to better predict snowmelt.

As snow and glaciers melt in these high mountains, the meltwater does not always run off into rivers, but can congregate in glacier lakes. It is important to understand the number and size of these glacier lakes, because they are potentially storing a lot of water that affects both the water supply in the region, and can even affect the amount of water that reaches the sea (and thus sea levels). Shugar *et al.*, 2020 ([Nature Climate Change](#)) studied this issue world-wide by using about a quarter million Landsat images from 1990 to 2018. The researchers studied not only glaciers on mountains, but also glaciers in Greenland. They took advantage of a widely-used algorithm that detects water in satellite images, the normalized difference water index, with some constraints to ensure their final dataset only included lakes formed by glacier melt. From the start to end of their study period, they found that the number of glacier lakes has increased from around 10,000 to around 14,000. Most of these lakes are found in Alaska, northern Canada, Scandinavia, Greenland, and Patagonia, and the fastest-growing lakes by area are found in Scandinavia, Iceland, and Russia.

One factor that will affect water supplies not just near mountains and glaciers but worldwide is evapotranspiration. Pascolini-Campbell *et al.* 2021 ([Nature](#)) examined global evapotranspiration trends. Heretofore, global measurements of evapotranspiration have not been reliable due to errors with model structures or upscaling of local observations. The researchers used data from GRACE and GRACE Follow-On to fill this gap with independent estimates of evapotranspiration. The results show that evapotranspiration from land is increasing globally, by 10% from 2003 to 2019, and the main driver is increased land temperatures.

Snow

[SnowEx](#) is a five-year program initiated and funded by WEC-THP to address the most important gaps in snow remote sensing knowledge and lay the groundwork for a future snow satellite mission. It focuses on airborne campaigns and field work, and on comparing the various sensing technologies, from the mature to the more experimental, in globally-representative types of snow. The following two publications are some of the latest results from SnowEx with the remainder of the section covering broader snow science.

Accurate measurements of snowfall are needed because when snow melts, it is often an important source of water for millions of people. Both papers described here used static ground instruments to measure snow accumulation and the expected meltwater, laying the groundwork for satellite measurements. The first paper looked at how the spruces, pines, and other trees often found in northern forests affect how much snow accumulates on the ground. Hojatimalekshah *et al.*, 2021 ([The Cryosphere](#)) used terrestrial laser scanning data (instruments mounted tripods) to measure the depth of snow both in open

areas, and under trees, in several sites spread across a high-elevation plateau in Colorado. As expected, open areas had more snow accumulation. Amongst trees, it was the trees with the most complexity in their number of layered branches that intercepted the most snow and kept it from accumulating on the ground. Zhu *et al.*, 2021 ([Water Resources Research](#)) used a wide array of ground-based microwave data collected at the Arctic Research Center in Finland to develop an algorithm to measure the amount of water in the snow, known as snow water equivalents (SWE). The more radar waves scatter from snow, the greater the water content. This can be measured using passive microwave instruments, but the estimates are not entirely reliable because the radar backscatter is also a function of snow depth, snow grain size, snow density, and other factors. The researchers combined the passive microwave sensors with information from active sensors, which allowed them to subtract other variables from the background scatter and isolate that which is specifically tied to snow water equivalents. However, while the first two years of estimates had reasonable results when compared to validation data of snow water equivalents, their algorithm underperformed during the third year. They suspect this might be because during that last year, the snow accumulation was not very thick, and the data retrieved at the various microwave frequencies was not distinct enough to be of use.

There were several snow-hydrology studies that focused on regional and more global scale, and the measurements were obtained through satellite sensors. Riggs *et al.*, 2020 ([Remote Sensing](#)) demonstrated that it is possible to create a global dataset of daily snow-covered land – an essential climate variable. Starting in 2000 and continuing to the present day, this dataset is built on images from MODIS and VIIRS sensors. This record is not yet long enough to reveal long-term trends, given the great amount of short-term variability. However, more VIIRS sensors are expected to launch clear to 2038, so the dataset can eventually be used to determine if the area of snow-covered land is decreasing globally, and if snow is melting earlier every spring. MODIS and VIIRS are different sensors, but the NASA team has worked to ensure that there can be continuity between data generated by each. This paper tried to test that by comparing same-day MODIS and VIIRS snow-cover data in the western United States. This dataset will be more effective the more accurate it is, and Rittger *et al.*, 2020 ([Water Resources Research](#)) sought to address some of the known errors in it. For example, clouds are still often confused with snow in satellite images, and trees and shrubs in a snowy landscape likewise interfere since a satellite sensor cannot see through a tree to the ground directly beneath it, and the projection of tree profiles also interferes when a satellite sensor is retrieving information at a sideways angle. Rittger *et al.*, 2020 uses additional information from MODIS in order to somewhat circumvent these issues. The advantage of their method is that no high-resolution data regarding the forest canopy is needed; rather, all the information can be retrieved directly from MODIS. These types of corrections are very important, since the amount of snow-covered land is information that is needed for many water resources models. When the input information is not accurate, it has been shown to actually decrease the performance of these models.

Even though Riggs *et al.*, 2020 ([Remote Sensing](#): above) found that the MODIS-based snow-cover record is not yet long enough to reveal long-term trends, and that not all of the Northern Hemisphere is reacting in the same way to climate change. However, there are definite and obvious trends in some areas, such as the western United States. O’Leary *et al.*, 2020 ([Physical Geography](#)) used daily MODIS snow cover to examine snow cover timing and duration in mountains like the Cascades, Rockies, and Sierra Nevada, and also areas that are lower elevation. People living in these areas are very dependent on snow for their water resources. Snow water is estimated to constitute 70% of the total water supply in this semi-desert area, so knowing how long the snow cover lasts and when it melts is very useful information. This paper only considered areas that had a substantial amount of snow for at least 10 years of the MODIS data record, and also where the commencement of snowmelt was clearly visible by the satellite sensors. Of these areas, they found that 7% were experiencing a significant trend towards earlier snowmelt. Most of this area was concentrated in mountains like the Southern Rockies and the Sierra Nevadas, and also in deserts like the Central Basin and Range (a desert between the Sierra Nevada and the Western Rockies) and the Mojave Basin and Range (also a desert, in southern California and Nevada). Interestingly, though, the snow in the Cascade Mountains of Oregon was found on average to melt later than normal. Thus, the trends are not uniform throughout the snowy parts of the western US and are location-specific. A caveat to note about this paper is that it made use of a newer MODIS data set that featured an advance over previous products in filling in parts of the satellite images excised due to clouds, and this dataset has not been extensively validated yet.

Surface water

WEC has invested in improving our ability to resolve surface water extent 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. WEC supports research that spanned a variety of surface water related science and technique development ranging from more comprehensive regional studies (i.e. Yukon and Mekong Rivers) to exploring new capabilities with NISAR and ICESat-2. Given that SWOT is anticipated to launch in 2022 we opted to focus on publications related to the mission.

SWOT Science

The upcoming SWOT mission is expected to significantly increase our understanding of river flow rates in ungauged basins, and water storage in surface water reservoirs. A considerable amount of SWOT-related research has been funded in recent years in

preparation for this mission. The following publications are a subset of the overall effort and focus on SWOT's measurement characteristics, temporal sampling for discharge, and the assimilation of SWOT data into hydrological models. In this section, we highlight a pair of publications that seek to better understand SWOT discharge measurements and how these measurements may improve regional discharge estimates. We also highlight a paper that looks at potential challenges facing SWOT's algorithms targeting lake/reservoir surface water extent.

Since SWOT is the first of a kind mission that has yet to launch, then it has been necessary to develop simulated SWOT-like data through either computer models or the collection of AirSWOT data to develop and test SWOT algorithms. Frasson *et al.* 2021 ([Water Resources Research](#)) uses simulated SWOT data created by hydraulic models for seven rivers to test discharge inversion algorithms. These algorithms will be key to fulfilling one of the key hopes of SWOT: its expected ability to estimate river discharge, especially in isolated, hard-to-access rivers. While SWOT will measure features of the river such as the width and the height of the water flowing, there are other factors, impossible to observe by satellite, that are also needed in order to convert the SWOT river observations into discharge estimates. These factors include the friction between the waterflow and the river banks, and the depth of the river bottom. Frasson *et al.* tested five different algorithms to estimate these more intangible parameters from simulate SWOT and found that these algorithms are better at tracking variation in discharge as opposed to the actual amount of discharge. That means that while SWOT will be able to elucidate when ungauged, isolated rivers have higher or lower flow, it will take more ground information to pinpoint an actual discharge estimate or range. In fact, SWOT-based estimates of discharge are expected to have 35% error. Even so, research is demonstrating the benefits these estimates will provide. Wongchuig-Correa *et al.* 2020 ([Journal of Hydrology](#)) showed that simulated SWOT data can improve the performance of hydrological river-based models. Using a model of the Purus River, which drains a portion of the Amazon rainforest, they showed that including simulated SWOT data improved the daily discharge model errors by 40%. This was true even though the SWOT will collect data in the Purus basin 1-3 times every 21 days. Those few "anchor" estimates of discharge from SWOT are able to improve discharge estimates for every day of the model output.

SWOT, in addition to gathering information on rivers, will also study inland lakes. Bergeron *et al.* 2020 ([Hydrology and Earth System Sciences](#)) used simulated SWOT data to probe how effective SWOT observations will be at capturing water depth in lakes stirred up by wind. For example, sustained winds in one direction can cause the lake in the water to be pushed in the same direction, congregating there and raising the height. Being able to track changes in lake height has ecological importance as the movement of water can cause spills into neighboring lakes, and can also expose mudflats. This study, focused on the Peace-Athabasca Delta area in Canada, found that if the SWOT overpass is able to capture the entirety of the lake, then it will be able to detect such wind-driven differences in lake height. In fact, it might give a more reliable indicator of how the lake has changed than what three gauges on the lake might provide. However, the researchers also flagged some potential issues with SWOT observations over lakes. For example, the simulated SWOT data was unable to identify the entire lake as water because some pixels

contain dark water. Such dark water, perhaps discolored due to algae, is hard to detect at low incident angles because of the low land-water contrast and the water pixels can be very noisy. This paper also studied a somewhat simplified scenario in which the winds were assumed to be at a constant velocity and direction; in cases where this is not true, there will be greater variations in the lake, and therefore greater errors if relying on partial SWOT coverage. The same caveat holds for some of the other simplifying assumptions made in this paper.

High Mountain Asia

The Himalayan mountain glaciers encompass 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 second HiMAT was selected and began new research in the spring of 2021 because the High Mountain Asia continues to be an important research theme.

One reason research is focused in the High Mountain Asia region is that the changing landscape sometimes can pave the way for tragedy. One such tragedy is the avalanche of February, 2021, on the Ronti Peak in India. Shugar *et al.*, 2021 ([Science](#)) examined this event in detail, making full use of all available data: satellite images, seismic records, numerical models, and even video posted by people caught up in the disaster. This avalanche was notable because the initial fall of the rock/ice mass was a 3700 meter vertical drop – a distance that has only been surpassed by two previous landslides. By doing a geodetic analysis and glacier thickness inversions, they determined that the avalanche mass consisted of 80% rock and 20% ice. However, due to the friction of the fall, the ice soon melted into water, which made the entire mass much more mobile. Thus, though the initial impact occurred in an isolated valley, the mass ended up traveling a great distance downstream and encountered two hydropower projects at which 190 workers died. Furthermore, by using satellite imagery, the researchers were able to find evidence of a river sediment plume about 150 km downstream from the avalanche source site, as well as a dust cloud that was deposited up to 500 m above the valley floor. The quick pace of the events precluded the ability to give proper warning, but in fact, optical feature tracking yielded signs that the rock mass on the Ronti Peak that eventually fell had started moving as early as 2016. It continued moving in the succeeding summers, opening up an 80-meter-wide gap in the glacier and bedrock. Since the stability of the glaciers in these high mountains is sensitive to climate change, there are elements of the avalanche that suggest climate played a role.

Climate also plays a role in the timing of the snowmelt in High Mountain Asia, and as an earlier paper described, this snowmelt can also occur earlier, and happen faster, when the

mountain glaciers and snows are coated with dust, black carbon, and other aerosols. Therefore, when the COVID lock-downs started in spring 2020, and air pollution fell across much of the world, this was evident in the High Mountains of Asia as well. In fact, Bair *et al.*, 2021 ([Proceedings of the National Academy of Sciences](#)) used satellite images to show that the snow on these mountains was the cleanest it had been for the past 20 years. This result held up in each of the two methods this paper pursued, one of which relied on the same MODIS-based snow product described above in the snow section. Hill *et al.*, 2020 ([Frontiers in Earth Science](#)) looked specifically at the water supply reaching Bhutan along the Brahmaputra River. People here use the water for drinking, farming, and for hydropower, and since the long-term supply of water provided through snowmelt might be affected by climate change, just how vital of a source is this? The paper used the trends in minimum snow and ice cover, retrieved from the MODIS Persistent Ice algorithm (based on the Snow Covered Area and Grain Size algorithm), as a starting point to investigate this. They combined this information with field work data on water chemistry isotopes and tracers that allowed them to estimate the proportion of water attributable to melting snow versus rainwater. They found that the Brahmaputra River was in fact dominated by rainwater, and the peak contributions from snow happened early in the monsoon season. Thus, for this particular area, even if the trends indicate that snow and ice cover decreases, the potential of increased rainfall might keep the water supply steady.

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 made it possible to begin to address global soil moisture issues at greater detail. Similarly, as algorithms improve for analyzing GRACE data, it is becoming possible to better characterize soil moisture contributions to GRACE time-series data. CYGNSS is now generating soil moisture datasets with daily and subdaily estimates of surface soil moisture for most of the subtropics and will expand our understanding of low latitude soil moisture dynamics. The highlighted publications below focus on improving and expanding soil moisture measurements made from GRACE and SMAP data.

Sadeghi *et al.* 2020 ([Journal of Hydrology](#)) used GRACE time-series data to estimate monthly change in on land water storage. Since such changes in water storage will of necessity often pass through the soil surface, the researchers took advantage of equations that convert GRACE observations into soil moisture estimates. GRACE-based estimates of soil moisture could complement estimates from SMAP in places like the Amazon rainforest and similar areas of very dense vegetation. In such areas, it is difficult to decipher if the L-band radar signal utilized by SMAP is resulting from soil moisture or is contaminated by moisture found on trees and bushes. Time series comparisons of GRACE and SMAP output per continent showed reasonable agreement between these two independent estimates of soil moisture. There remain gaps with both these methods

however, in that they are not adept at measuring soil moisture when the ground is frozen, nor in dry desert areas. GRACE, for example, returns its most accurate estimates when the signal is large in magnitude. Therefore, a dry area like a desert does not have enough soil moisture to cause a signal that GRACE can detect.

Gao *et al.* 2020 ([Remote Sensing of the Environment](#)) similarly tried to expand the availability of remotely-sensed soil moisture algorithms by proposing a new method for SMAP. The conventional algorithms that convert SMAP observations into soil moisture require proper calibration of several land variables: the direct upward emission of the soil (also known as roughness), the direct upward emission of the vegetation, the vegetative optical depth, and the soil temperature. However, there is global uncertainty in all these parameters, and this produces a key source of error in SMAP soil moisture estimates. The new algorithm proposed by Gao *et al.* 2020 neatly bypasses this challenge by not requiring empirical relationships to estimate these parameters, and also not requiring land cover maps. This algorithm, however, is only able to measure the soil moisture in situations where observed emissivity is changing significantly over time, and it relies on the assumption that the soil roughness and vegetation parameters are relatively constant over a period of time. The researchers tested their algorithm over Australia and found that the resulting soil moisture estimates were in good agreement with official SMAP products, except in some parts of the country, including the coast. Because it relies on steady vegetation parameters, this algorithm is not as effective for farm fields during growing or harvest seasons. They also compared their soil moisture estimates to field data, and found the performance of the new algorithm can surpass that of the current SMAP products. This algorithm is still in the early stages of testing, cannot yet be used to create a global soil moisture product, and future investigations of its performance in areas with different land cover gradients are of special interest.

While CYGNSS was designed to utilize reflected GPS/GNSS (GNSS-R) signal off the ocean surface to advance our understanding of ocean and weather process, researcher evaluating the GNSS-R signal over land found that the signal provided a wealth of information about soil moisture dynamics with subdaily observations. Kim *et al.* 2021 ([Environmental Research Letters](#)) is the first known global assimilation of GNSS-R based soil moisture observations in Land Surface Model (LSM). Their analysis integrated CYGNSS and SMAP data using a triple collocation analysis approach and found that assimilating subdaily soil moisture data can significantly improve (61.3%) the fractional mean square error of soil moisture predictions except in densely vegetated areas. They determined that dense vegetation canopies can propagate erroneous soil moisture information to the LSM.

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. Data from GRACE and GRACE-FO provides global measurements of mass change, including the redistribution of water (solid and liquid). Both techniques measure changes in water storage and not the absolute volume. The following publication by Neely *et al.* utilized geodetic measurement techniques (InSAR, GPS) to better characterize and understand spatial and temporal variations of groundwater processes in California's Central Valley.

The desert-like area of central California is heavily dependent on groundwater to grow crops, especially during dry years of less than average precipitation. However, this reliance on groundwater is not without consequences, since groundwater pumping often causes aquifers to shrink and the land above to sink. While this link is firmly established, Neely *et al.* 2021 ([Water Resources Research](#)) wanted to examine the opposite circumstance: when groundwater aquifers are refilled during wetter-than-average years, does that cause the land to life back up? They studied two hydrological years over California's Central Valley, 2016 (a dry year) and 2017 (a wet year). They used both interferometric synthetic aperture radar data from Sentinel-1, as well as data from 89 continuous GPS stations. Combining the data from these two independent sources improved the accuracy which may be affected by atmospheric, orbital, and processing errors. The researchers found that during the dry year, rates of land subsidence were twice as high compared to the wet year. Interestingly, though, the rates of land rising back up (rebound) were the same during both years (a peak seasonal amplitude of about 35 mm), and in both years, land uplift occurred alongside rivers where streamflow from the Sierra Nevadas is a source of groundwater recharge. The most uplift during the dry year occurred during the spring, while in the wet year, it was concentrated in the summer. However, groundwater recharge or extraction is not always mirrored by a corresponding fall or rise in the land. For example, the aquifers beneath the city of Fresno stands is comprised of coarse-grained sediments that don't easily consolidate and collapse when groundwater is withdrawn, which is seen in aquifers with fine grained rock units. Because of issues like this, it is not possible to relate the fall or rise of the land to absolute changes in groundwater volumes without additional information.

Water – Ecosystem / Evapotranspiration / Drought / Wildlife / Water Quality

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. The vegetation water content of ecosystems is a living water reservoir which contributes to moving water through the global water and energy cycles through evapotranspiration (ET). Furthermore, anthropogenic activities such as agriculture production contribute to the movement of water through the global water budget and energy cycles. A new section added to this year's GPRA covers a series of publications that begin to look at the interplay between water and wildlife.

Wildlife and Water

Animals are often on the move, searching for the essentials they need to survive. One of these essentials is of course water. But aside from using water to drink and wash, water in other stages of the water cycle can also impact animal movement. For example, snow in the Arctic areas and boreal forests and the associated weather patterns can be a factor around which wildlife must plan their feeding, birthing, and sheltering habits. Deep snow may cover the grasses and other vegetation mammals feed on during the winter, leading them to seek out areas where sharp winds have scoured the snow away. Warmer temperatures and earlier snowmelt can trigger some animals to give birth to their spring young earlier, and birds to migrate at unaccustomed times. The next few papers provide insight into what drives animal movement patterns in the north, patterns that could well be affected with the changing climate. Since the Arctic areas are experiencing warming temperatures at a faster rate compared to the global average, then climate change might prove a particularly sharp disrupter of Arctic animal patterns.

More data is now available than ever before to track animal movement with the creation of the Arctic Animal Movement Archive (AAMA). Davidson *et al.* 2020 ([Science](#)) explores this new archive, which contains 200 tracking studies of both sea and land animals. It contains more than 15 million occurrences of 8000 individual animals from 86 species, starting from 1991 to the present. One species included is the golden eagle, a bird which migrates north to spend the summer and breed in the Arctic. By examining AAMA data, the researchers found that over 25 years, the mean date of arrival had slowly changed so as to take place half a day earlier. While this might not seem like an overwhelming change, when they further examined the arrival patterns by eagle age classes, they found that a warmer-than-usual winter, resulting in a warmer and drier climate with less snow, led to sub-adult eagles to have a mean date of arrival over eight days earlier. Full adult eagles did not show this same link to warmer-than-average winters. This finding indicates the need for animal data that is individualized by generation. This archive also has enabled the first continent-scale study to look at how caribou in northern Canada are adapting to warmer winters. Data on almost a thousand caribou from 2000 to 2017 indicate that certain classes of caribou – those clustered on barren-ground habitat and those in the northern boreal forests – had a trend towards earlier births. The Arctic Animal Movement Archive will enable more such studies.

One particular animal – a species of sheep that lives in Canada and Alaska – were studied in depth by two papers. Dall's sheep, so named after a 19th century American naturalist, are wild sheep with coats of wool often the same snow-white color as their winter surroundings. These papers examined data on sheep patterns, a valuable endeavor since the population has been falling. They also used snow evolution models in order to match weather and snow characteristics to the data on sheep habits and births. The snow evolution models were fed in some cases by weather inputs from NASA's MERRA-2 dataset, as well as topographic information from JPL's ASTER instrument. Aycrigg *et al.* 2021 ([PLOS ONE](#)) coupled their snow evolution model with data on 20 adult female sheep collared with GPS instruments that gave their position every seven hours from 2005 to 2008. They used the GPS locations to study the sheep preferred habitat by

season. They found that in the winter and the spring, the highest influence on sheep preferred habitat was the need to be near terrain from which they could escape predators easily. During the winters, the sheep also chose areas at which the grass, sedges, and herbs that they eat would be accessible. This normally meant steep areas with high winds that could shift away deep piles of snow, and areas with great sunlight warmth. Such sunlit areas would also mean warmer shelter for the baby lambs once they were born in the spring. Likewise, Cosgrove *et al.* 2021 ([PLOS ONE](#)) further looked at the link between weather, snow, and the survival of baby lambs. Based on 19 years of survey data on sheep populations collected by airplane, they found that extreme weather in the autumn – both in terms of cold temperatures and deep snows – were the main factors out of all the data they had that would cause a marked decline in the lamb survival. It was a bigger factor than deep snows and cold temperatures in either the winter or the spring, just before the lambs are typically born. The paper authors surmise this is because extreme fall weather means that the extreme conditions last the entire winter and spring, and the earlier start means the mother sheep are struggling for more months to find food and to move through deep snowdrifts. This impacts the weight of the baby lamb and the strength of the mothers to protect them from predators, nurse them, and gather food for them. This paper also suggests that these patterns can be very site-specific, meaning sheep at high elevations can exhibit different patterns compared to sheep at lower elevations.

Water Quality

The ability to accurately estimate different aspects of water quality in lakes, rivers, and coastal waters from satellites would be a true advance in remote sensing. However, this is a difficult endeavor and still a point of research due to the atmospheric and hydrologic factors that complicate the optical signal over these waters. For example, over clear ocean water, the dominance of non-absorbing aerosols means that existing processes for correcting atmospheric interference with the satellite signal are sufficient. Inland and coastal waters do not have this simplicity; there, both land- and ocean-originating aerosols can mix and create diverse conditions that current aerosol models do not capture. Furthermore, ocean waters have an additional simplicity when it comes to estimates chlorophyll *a* concentrations via satellite. There, this can be accomplished using the blue-green light wavelength band ratios, since other material like detritus and colored dissolved organic matter will often co-vary with phytoplankton. This is in contrast to inland and coastal waters, where the color of water is also affected by organic matter, dissolved matter, and inorganic particles, none of which co-vary with phytoplankton. The following papers try to explore these complications associated with inland and coastal waters and present advances and investigations of algorithms meant to estimate water quality there.

When it comes to inland and coastal waters, there is often great interest in having accurate estimates of concentrations of total suspended solids (TSS) and chlorophyll *a*.

Each of the following papers focused on one of these. First, Jiang *et al.* 2021 ([Remote Sensing of Environment](#)) presented a new method for estimating TSS in all waters, from clear to extremely turbid. This method involves first classifying water according to its level of turbidity, then assigning a separate light wavelength to study each level, and creating a relationship between TSS and particulate backscatter for each. Water samples taken worldwide were used to validate the method. Compared to three other methods, this model returned better results across all metrics used to evaluate model performance, which they then further applied to images from MERIS and Ocean and Land Color Instrument (OLCI). Smith *et al.* 2021 ([Frontiers in Remote Sensing](#)) presented a new machine-learning based method for estimating chlorophyll *a* concentrations. They used a global set of paired reflectance and chlorophyll *a* water samples, as well as chlorophyll *a* concentration-satellite data match-ups (satellite data from Landsat 8). They used these two datasets to train several machine learning models, including a Mixture Density Network. While they found their method to be a promising step forward, the next step would be to create a global-scale model with the necessary inputs to learn the relevant covariances in all atmospheric conditions.

Since so many errors when it comes to remote sensing of both TSS and chlorophyll *a* stem from inadequate atmospheric corrections, a large group of scientists banded together to investigate the performance of current corrective options in a systematic and orderly way. Pahlevan *et al.* 2021 ([Remote Sensing of Environment](#)) created a dataset of water samples of both TSS and chlorophyll *a*, paired with the radiometric reading. They compared this water field data to satellite matchups originating both with Landsat 8 and with Sentinel-2, by using eight different atmospheric correction algorithms. They found that there is no single preferred corrector or solution for all situations; rather, one must choose the corrector based on how the strengths of each align with one's own specific scientific objective and application. The paper also provides a ranking of how each algorithm performed for each optical water type. More work is needed in this arena, and the coming launch of some hyperspectral missions may be of help.

Section 1.1.8.6 Weather and Atmospheric Dynamics Focus Area

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 observe weather systems, produces carefully calibrated data products for scientific investigations including characterization, understanding, prediction and applications, develops new observation platforms and instruments to expand the observations, performs field campaigns to better understand weather processes, studies the behavior of weather systems using integrated modeling and data assimilation systems, and transitions the scientific understanding and knowledge to operational weather forecast organizations.

To demonstrate progress in **characterizing the behavior of the Earth system, including its various components and the naturally-occurring and human-induced forcings that act upon it**, 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). After data products become available, WAD funds scientific investigations that analyze the data products to characterize the behavior of the Earth system with emphasis on phenomena identified in satellite observations. Two of the major long-term environmental data sets developed for the research communities highlighted in this report are the Integrated Multi-Satellite Retrievals for GPM (IMERG) and Community Long-Term Infrared Microwave Combined Atmospheric Product System (CLIMCAPS). These community data sets are addressing the weather research and development communities' needs for data analysis and for comparison to modeling results. While IMERG is a long-term global precipitation data set, the CLIMCAPS is a long-term atmospheric state data.

Characterizing the Behavior of the Atmosphere:

Long-term atmospheric state data record development: CLIMCAPS Version 2 for Aqua was successfully delivered to and implemented at the GES DISC and its sounding retrievals and cloud cleared radiance products are available to the public for the full record (Sep. 2002 to present) of the Atmospheric Infrared Sounder (AIRS) and for Sep. 2002 to Sep. 2016 for the AIRS + AMSU (Barnet 2021a). Level-3 products for the full missions of CLIMCAPS Aqua AIRS+AMSU, CLIMCAPS Aqua/AIRS-only, CLIMCAPS/S-NPP NSR (2012-present), CLIMCAPS/S-NPP FSR (11/2015-5/2021), and CLIMCAPS JPSS-1 were also made public (Barnet 2021b). CLIMCAPS differs from other operational products in that it uses MERRA-2 as its first guess for temperature, moisture, and ozone and, as a result, the CLIMCAPS products have significantly improved stability and error estimates for all products retrieved. CLIMCAPS methodology significantly improves the continuity over the full record of hyperspectral infrared and microwave sounding products for Aqua, S-NPP, and JPSS-1 that can be employed to improve the understanding of weather and atmospheric dynamic processes and contribute to the understanding of changing atmospheric composition through its simultaneous retrieval of many important weather and climate-relevant gases.

Algorithm to fuse multiple instrument radiance observations: Construction of the first 18 years of a CLARREO-like (IR only) long-term climate radiance records was completed this year with the production of CHIRP (A Climate Hyperspectral Infrared Radiance Product) at the GESDIS. CHIRP combines AIRS with the CrIS series of sensors into a single homogeneous (common spectral response with instrument bias offsets removed) radiance record designed for high-stability climate trending, anomalies, and extreme event detection. The CHIRP ATBD, Strow et. al. 2021, highlights the accuracy of the conversion of AIRS and CrIS to CHIRP format. This approach allows climate trending in radiance space in order to avoid bias errors in both the instrument, the radiative transfer algorithms, and from a-priori errors in retrievals. The stability of the AIRS contribution to CHIRP was published in late 2020 (Strow et. al. 2020) which compared radiance anomaly retrievals of carbon dioxide trends to in-situ measurements of carbon dioxide trends. Application of the radiance anomaly trend approach to global surface temperature trends have shown that there are a number of significant errors in the AIRS Level 3 surface trends, partially due to the use of AIRS shortwave channels that have drifted, and partially due to poor trends in regions of highly variable cloudiness (roaring 40's, warm pool regions). The main impact of the surface temperature work suggests that the arctic is warming about 30% slower than earlier work, while sea-surface temperatures north of Antarctica are not cooling as strongly as predicted with AIRS L3 data (and more similar to GISS estimates).

Advanced microwave sounding algorithm development: The "Retrieval Algorithm for Microwave Sounders in Earth Science", RAMSES-II, was completed and delivered to the Sounder SIPS, along with an assessment report and documentation (Roman et al., 2021) "Test Report of Performance of RAMSESII-SNPP Retrievals", June 2021, on GES-DISC). It is in the process of being operationalized at the GES DISC and released to the public. RAMSES-II is NASA's only stand-alone ATMS retrieval system and will initially be used to process ATMS data from S-NPP and NOAA-20 (JPSS-1) as well as future JPSS satellites as they are launched. RAMSES-II can also be configured to process AMSU data from earlier NOAA satellites, which would create a continuous and consistent microwave sounder data series from 1998 into the 2030's and beyond. Primary data products are vertical profiles of temperature and cloud liquid water.

Characterizing Atmospheric Boundary Condition:

CYGNSS for Characterizing Soil Moisture Content: Currently, the ability to use remotely sensed soil moisture to investigate linkages between the water and energy cycles and for use in data assimilation studies is limited to passive microwave data whose temporal revisit time is 2–3 days or active microwave products with a much longer (>10 days) revisit time. Chew and Small (2020) describe a new soil moisture data product for the upper 5 cm of the soil surface which is derived from the Cyclone Global Navigation Satellite System (CYGNSS) constellation. The product is gridded to 36 km in sparsely sampled 6-hour intervals for +/- 38 degrees latitude from 2017–2020. The product was developed by calibrating CYGNSS reflectivity observations to soil moisture retrievals from NASA's Soil Moisture Active Passive (SMAP) mission. Retrievals were validated against observations from 171 in-situ soil moisture probes, with a median unbiased root-

mean-square error of 4.9% by volume. The new soil moisture product is complementary to SMAP, with a larger random noise component but faster revisit times than passive microwave remote sensing currently provides.

Better Characterization and Understanding of Convective Cloud and Precipitation:

Remote Sensing and In-Situ Measurements of Snowbands Within Winter Cyclones: The Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) is an Earth Venture Suborbital-3 (EVS-3) field campaign to study northeastern US snowstorms. Snowfall is often organized in narrow banded structures called snowbands and the goals of IMPACTS are to understand the mechanisms associated with snowband formation, organization, and evolution using airborne remote sensing measurements from above the storms and in situ microphysics measurements within the clouds. Data from the first deployment were collected in winter 2020 and the first half of the reporting period was spent quality controlling the vast dataset and uploading the data to the DAAC hosted by GHRC. Several manuscripts are currently in different stages of preparation and review, but not accepted at this time. An ongoing study investigates the microphysical properties within regions of enhanced dual-frequency ratio (DFR). Regions of prominently higher Ku- and Ka-band DFR were characterized by larger mass-weighted mean diameter, smaller effective density and lower normalized intercept parameter than in regions of lower DFR. These microphysical characteristics are consistent with significant aggregation and are related to increased snowfall rates on the ground. The IMPACTS 2020 campaign data is available at GHRC DAAC (https://ghrc.nsstc.nasa.gov/uso/ds_details/collections/impactsC.html).

Precipitation radar algorithm development using path-integrated attenuation measurements: The GPM DPR instrument performs the first satellite based, nearly global (66S-66N) measurements of Ku and Ka band radar reflectivity. This dataset is still being explored and new pathways for using the dual-frequency data to retrieve precipitation characteristics are being developed. One of the most important inputs that the DPR rainfall retrieval algorithms use, aside from the reflectivity profiles, is the path-integrated attenuation (PIA) estimate. The use of the PIA has a long heritage from the TRMM algorithms and is needed to correct the reflectivity profiles for attenuation and provide an independent constraint on the total liquid water path, which is highly correlated with the surface rainfall rate. Meneghini et al. (2021) provide an overview of the latest improvements to the PIA algorithm for DPR. This algorithm works for one or both frequencies and invokes several methods for estimating the PIA, each of which has strengths and weaknesses depending on the surface type and rainfall intensity. The operational algorithm uses a weighted blend of these methods to provide an optimal estimate for input to the rainfall retrieval algorithms. In another study by Kobayashi et al. (2021), the range derivative of the dual-frequency ratio was used to infer the attenuation profile. This is complementary to existing methods that estimate the path-integrated attenuation and is particularly useful for discerning precipitation phase.

Measurements of snowfall from spaceborne radars: The GPM DPR Ku and Ka band reflectivity profiles provide a strong theoretical constraint on the snow particle size

distribution (PSD). However, most of the operational algorithm development focus has been on providing accurate rainfall rates since the vast majority of global precipitation falls as rain. Chase et al. (2021) found some systematic deficiencies in the snow profiles retrieved by DPR, stemming from sub-optimal algorithm assumptions about the snow PSD. By replacing these with a neural network-trained relationship based upon in-situ aircraft observations, they were able to improve the performance of a DPR-like algorithm with respect to the retrieval of snow PSD characteristics.

An alternative approach to precipitation retrievals from spaceborne radars: The GPM DPR precipitation algorithm is a physically based profiling algorithm that aims to provide a precipitation profile that is consistent with the observed Ku and Ka band reflectivity profiles and path-integrated attenuation estimates, guided by several assumptions about the particle size distributions and hydrometeor type profile. An alternative type of algorithm, the Bayesian correction (BC) was developed by Ma et al. (2020) to improve DPR precipitation estimates by developing a statistical relationship between the DPR profiles and ground radar (GR) measurements. The GR rainfall estimates have the advantage of higher horizontal resolution and dual-polarization information, which can constrain the PSD assumptions and non-uniform beam filling that must be assumed by the DPR algorithm. By statistically correcting the DPR retrievals with the BC method, the study demonstrated improved performance of the DPR retrievals over the southeastern United States.

Measuring rainfall from passive measurements of changes in surface emissivity: The passive microwave radiometers used for precipitation retrieval in the GPM constellation include channels that are sensitive to surface characteristics in the absence of precipitation. These include soil moisture, which is directly affected by recent rainfall. You et al. (2021) developed an algorithm to use changes in the 19 GHz emissivity, a common frequency on 10 radiometers in the GPM constellation, to infer rainfall between consecutive clear-sky overpasses. A notable outcome of this study was that minimizing the time between overpasses had a large impact on retrieval performance: using all 10 radiometers in the GPM constellation (~3 hours between overpasses) was better than the 5 conical imagers (6 hours) or GMI only (> 1 day).

Using dynamic surface information to improve retrievals of precipitation: The algorithm used for passive microwave precipitation retrieval by GPM (GPROF), is a Bayesian method that uses databases of observed precipitation and associated brightness temperatures. These databases are divided by land surface type, surface temperature, and column water vapor, and the surface type is assigned to an observation by a static map that depends on month and snow cover presence (informed by ancillary data). This has drawbacks in regions where the surface emissivity can change rapidly and drastically, e.g., due to floods or snowmelt. Ringerud et al (2021) investigated the use of dynamic surface and water vapor classes that are derived directly from GMI observations in and near precipitation, instead of the static classes. They found that this method reduces false detection of precipitation

Estimating precipitation vertical profile information from passive microwave sensors:

Although the most commonly used output from the GPROF passive microwave precipitation retrieval algorithm is the surface precipitation rate, GPROF also produces profiles of condensed (ice and liquid) water content. Utsumi et al. (2020) compared these profiles against an alternative technique (emissivity principal components - EPC) and validated both with the GPM DPR-retrieved profiles (since the DPR measures reflectivity profiles directly, this should provide an accurate basis for comparison). They found that GPROF tends to overestimate the water content in the profiles while EPC underestimates compared to DPR. The authors found that some of the EPC bias could be mitigated by better partitioning convective and stratiform precipitation, suggesting that there is a different relationship between the brightness temperatures and condensed water profile in the two different precipitation types.

Passive microwave land-surface algorithm information: Although the GPM mission is focused on precipitation detection and measurement, the vast majority (~90%) of the earth's surface is not experiencing precipitation at any given moment. Munchak et al. (2020) sought to make use of these clear-sky measurements to improve the characterization of surface properties for the GPM precipitation algorithm and other applications. To that end, they developed an extensive database of surface emissivity (retrieved from GMI) and backscatter (measured by DPR) over 5 years. This database was used to derive joint emissivity-backscatter based surface classifications, covariances between emissivities and backscatter, and relationships between emissivity and previous rainfall and snow water content.

Multi-satellite precipitation product landslide applications: Satellite multi-sensor precipitation products (SMPPs) have the potential to fill in precipitation data for various applications where surface gauge data are not sufficient, but uncertainty in the SMPPs has hampered such use. Hartke et al. (2020) demonstrate how considering the uncertainty in SMPPs can improve predictions from a landslide hazard model over the mountainous southeastern U.S. An error formulation was trained with coincident Integrated Multi-satellite Retrievals for Global Precipitation Measurement (GPM) mission (IMERG) and ground-based gauge precipitation data and input to a probabilistic version of NASA's Landslide Hazard Assessment for Situational Awareness (LHASA) model. The additional uncertainty information allows the probabilistic LHASA to capture more landslides than the existing deterministic version with lower false positive rates, particularly in high hazard nowcast categories. As well, the study showed that sparse ground truth data in a regionalized training scheme provided nearly identical improvements in LHASA performance to a localized scheme using many more validation points. This makes it likely that LHASA trained for SMPP uncertainty in the U.S. is viable in many places around the world. The authors point out that ensemble forecasts from numerical models might well provide similar probabilistic information, and that uncertainty-aware schemes might be equally helpful in other environmental prediction models, such as for flood forecasting.

Multi-satellite precipitation estimates of precipitation trends: One of the key questions in climate studies is the trend in various parameters. While global temperature is trending

upward at a rate that outstrips the interannual variation, this is much less true for global precipitation. Rather, regional trends of opposing sign tend to be large, but off-setting. In addition, Kazemzadeh et al. (2021) examined the possibility that the long-term variations are not simple linear changes with time. They employed the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) quasi-global precipitation product for the years 1998-2017, which is not strictly a climate product and only covers 20 years but served to give a first cut at how precipitation has changed in the recent climate by region. They found that 12.3% of grid box time series across the globe have significant trend at 0.05 significance level, evenly split between positive and negative trends. In all continents except Asia, decreasing trends were found to cover larger areas than corresponding increasing trends. Linear trends dominated in the equatorial (80.4%) and warm temperate climate zones (77.7%), while the colder climate zones had less linear change (68.9%). Increasing trends tended to be more significant in Asia and arid climate over the last 20 years. Although linear change in precipitation dominated the global map at 80% coverage, nonlinear trend types were important regionally, with quadratic and cubic contributing 11% and 9% coverage, respectively, focused on arid regions. These results provide a key test dataset for climate model validation and can inform long-term water resource planning around the globe.

Radar detection capabilities and issues for light rainfall: The only two scanning precipitation radars that have flown in space, namely the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) and the Global Precipitation Measurement (GPM) mission Dual-frequency Precipitation Radar (DPR), have known limitations for detecting light, near-surface precipitation. Kidd et al. (2021) assessed these shortcomings for three sites in the British Isles using coincident Micro Rain Radars (MRR) and surface radars. This region was chosen because it frequently experiences light, shallow precipitation that typifies many mid- and high-latitude precipitation regimes. The study showed that the PR and DPR can only detect about 62% and 75% of events at the sites, respectively, due to the radars' sensitivity thresholds of about 0.5 and 0.2 mm/hr. The PR and DPR cannot use the lowest few range bins due to contamination by surface clutter. In this study, this excludes the first 1000 m at nadir, increasing to about 1500 m at the edge of the radar swath or higher in complex terrain. At the MRR sites, typically only 80% of the cases reach to or above 1000 m, and only 64% go to or above 1500 m. Taking sensitivity and height together, at the MRR sites only about 62% to 63% of cases with surface precipitation show precipitation above 1000 m at intensities ≥ 0.2 mm/hr, falling to about 52% to 53% ≥ 0.5 mm/hr. Thus, in these typical mid- to high-latitude cases, the PR and DPR may not be able to observe about half of all precipitation occurrences, although the observable cases comprise the heavier events, and so the accumulations are more nearly correct.

Precipitation measurements provide information on tropical cyclone formation: Wang et al. (2020) used GPM DPR data to compare the characteristics of convective (vertically oriented, strong vertical air motions) and stratiform (horizontally oriented, weak vertical motions) precipitation in storms systems that went on to form TCs (termed developing systems) and those that did not (non-developing). In general, developing systems had slightly more areal coverage of convective rainfall and substantially more stratiform

precipitation coverage than non-developing storms. In addition, the mean rainfall intensity was significantly larger in both convective and stratiform precipitation areas in developing TCs. The greater coverage and intensity of stratiform precipitation would favor developing of a stronger mid-level vortex while strong convective rainfall would generally favor lowering of that rotation to the surface.

Characterization or rainfall asymmetries in tropical cyclones: Liang and Chan (2021) used GPM IMERG data to re-examine the asymmetrical distribution of precipitation around TCs associated with vertical wind shear. They suggested that in the inner-core region, radius < 150 km, precipitation is maximum on the downshear-left side of the storm when shear is defined conventionally as occurring over the 850-200 hPa layer. However, for the outer-band region, outside of 150 km, the effective shear layer is closer to 900/850 to 400 hPa. The higher top of the effective shear layer in the inner core versus the outer region is likely tied to the greater depth of the convection in the inner core region.

Multi-satellite precipitation product skill in tropical cyclones: IMERG-estimated rainfall during hurricane events were compared to ground-based radar data by Ayat et al. (2021) and demonstrated that passive microwave estimates within the IMERG product tend to underestimate storm precipitation area size, likely by not adequately detecting lighter rainfall. These microwave estimates tend to have smaller areal coverage, but greater intensity, than estimates from IMERG morphed or infrared-based estimates. The study also examined the quality of precipitation estimates among all microwave sensors and found that imagers provided better estimates than sounders. Yuan et al. (2021) compared IMERG and TRMM Multi-satellite Precipitation Analysis (TMPA) TC rainfall estimates to surface gauge data, finding that IMERG provided improved estimates relative to TMPA. However, both products tended to underestimate extreme precipitation in TCs.

Hail detection and climatologies based on satellite observations: Three new studies examined algorithms for the detection of hail from GPM data. Laviola et al. (2020) present a new method for detecting hailstorms using satellite microwave radiometers currently in orbit. Specifically, the authors use a probability-based model originally designed for the Advanced Microwave Sounding Unit-B (AMSU-B) and the Microwave Humidity Sounders (MHS)-based radiometers that has been fitted to the observations of all microwave radiometers onboard the satellites of the Global Precipitation Measurements (GPM) constellation. The results show that this approach offers the potential of retrieving a uniform and homogeneous hail dataset on the global scale that can be beneficial for applications, in particular hailstorm events in South America. Bang and Cecil (2021) evaluated passive-microwave hail detection algorithms using a proxy for hail occurrence from GPM DPR reflectivity information. In general, passive microwave algorithms using information from both the 19 and 37 GHz channels more tightly constrains the distribution of reflectivity at upper levels and shows less geographical variability compared to algorithms using on 37 GHz information. Studies by Seiki (2021) and Le and Chandrasekar (2021) use DPR reflectivity and dual-frequency ratio (DFR) information to infer graupel and hail occurrence, as validated by ground-based radar data. Seiki's (2021) method relies on filters for removing contamination from

melting snow and rain but allows for estimates of hail occurrence around the globe and as a function of height, with hail being frequently observed in a thin layer near the melting level. Le and Chandrasekar's (2021) method relies on a precipitation type index that uses echo-top height along with reflectivity and DFR and produces a fairly distinct separation between the detection of hail/graupel and snow. Hail detections are compared to a number of events observed by ground-based radars and a global climatology shows reasonable agreement with prior estimates using combined passive and active measurements.

Characterization of extreme precipitation events: Several studies highlight the use of GPM data to characterize extreme precipitation events around the globe. Wang and Tang (2020) used 22 years of data from TRMM and GPM combined to examine both extreme precipitation rates and extreme convective storms (in terms of storm depth). Extreme precipitation rates are often found over ocean and over tropical land regions while extreme convection is concentrated over land areas. Extreme events of both types are typically most frequent during the warm season and exhibiting a strong diurnal cycle over land. Navarro et al. (2020) demonstrated that IMERG estimates reasonably captured rainfall from extreme precipitation events over the southern slopes of the Pyrenees. Reanalysis data often performed better for winter storm events while IMERG was better for warm season rainfall. Hourngir et al. (2021) use the DPR-GMI Precipitation Feature Database to characterize intense Mediterranean storms and examine variations by season, time of day, and land surface type. Diurnal variability is comparable to that seen elsewhere, with an afternoon peak over land and small early morning peak over ocean. Hailstorms show preferred occurrence over land during summer but over ocean during fall months.

Satellite Validation

Validation of satellite rainfall using the U.S. national radar network: A major current effort for GPM validation follows the work of Schwaller and Morris (2011) who developed the GPM Validation Network (VN). That effort has moved from NASA GSFC to NASA MSFC and has expanded significantly since its inception in 2011. Originally, the VN network was used to compare/validate only reflectivity and rain retrievals with TRMM single-frequency radar data; however, with the readily available dual-polarimetric radar from the NEXRAD network and the dual-frequency GPM/DPR, additional parameters detailing the drop size distribution (DSD) such as the median drop diameter (D_m) can also be validated. Gatlin et al. provide an update and analysis of VN comparisons between GPM and ground-based radars (mostly National Weather Service NEXRAD). To date, over 100 radar sites are used to compare to GPM overpass data. The GPM VN provides quality-controlled dual-polarimetric radar moments for use in providing reference estimates of the DSD which are carefully geometrically matched with the GPM core satellite measurements for evaluation of the GPM algorithms. Gatlin et al. (2020) compared DSD retrievals from both the DPR and combined GMI/DPR algorithms and found that they both provided biases of D_m of only 0.2 mm, which is well below the GPM Level II requirements of 0.5 mm.

Validation of multi-satellite precipitation products: Wang et al. (2021) provided validation study of both the integrated multi-satellite retrievals for GPM (IMERG) and its predecessor, the Tropical Rainfall Measuring Mission (TRMM) multi-satellite precipitation (TMPA) data. To perform a validation over CONUS, they used data from NSSL's Multi-Radar, Multi-Sensor (MRMS) precipitation products. Their study evaluated two satellite-based precipitation products TRMM 3B42 V7 and GPM IMERG V06B using MRMS as the reference over CONUS for the 55-month period (June 2014 to December 2015, June 2016 to July 2017, and March 2018 to December 2019). They found that all of the satellite and ground-based products were spatially consistent, albeit with some differences. They also found that the GPM IMERG showed substantial improvement over the TRMM TMPA. They also noted that missed precipitation over mountainous regions (e. g., the western US) remains a challenge for ground-based estimates and also for satellite retrievals over mountainous regions with ice/snow coverage.

Using airborne field campaign data to validate space-borne precipitation measurements: Durden et al. (2020) compared GPM/DPR observations during the GPM OLYMPEX field campaign (Winter 2015-2016, Washington, USA) to airborne measurements obtained by the 3rd Generation Airborne Precipitation Radar (APR3) to better understand how resolution affects precipitation retrievals. They used two cases, one within the warm sector of a mid-latitude cyclone, and the other a small isolated convective cell. Given the relatively coarse GPM/DPR pixel resolution of about 5 km at nadir, the higher resolution APR3 is able to measure many more pixels for each GPM/DPR pixel, and hence is able to investigate the variability of precipitation within each GPM/DPR pixel. Their overall results showed that the DPR performs well in both the detection of precipitation and determining the vertical structure; however, resolution effects were evident. Specifically, the maximum GPM/DPR reflectivities tended to be lower as was the path integrated resolution (PIA). In some cases, the GPM/DPR measured lower storm heights and misclassified the precipitation type, especially in cases where large horizontal variability is present.

Validation of snowfall estimates using surface data: In a continental U.S. (CONUS) wide validation of snowfall estimates over land, Kongoli et al. (2020) used in-situ surface data collected over the 2014-2015 and 2015-2016 winters to compare to high-frequency passive microwave retrievals by GPM. They showed that the polarization difference at 166 GHz provided the highest correlation to surface-measured snowfall than that from the 89 GHz polarization difference. They applied a logistic regression model to the matched data, which yielded a snowfall classification rate of 69%. Their results also showed that the data from the horizontal polarization at 166 GHz yielded the most contribution to their model. Additionally, adding the 183 GHz data to the model yielded a classification rate of a rather remarkable 73%.

Validation of raindrop particle size distributions: Adirosi et al. (2020) used a loose network of laser-type disdrometers in Italy to help validate GPM/DPR measurements over the seven years since launch. Their comparisons found consistency between the GPM algorithms; however, their results suggested that the dual-frequency algorithms

performed somewhat better than the single-frequency algorithms. Their analyses compared key drop size distribution (DSD) variables, assuming that their relationships follow a normalized Gamma model. These variables are: reflectivity (Ka and Ku); the normalized intercept, N_w ; rain rate, R ; and the mass weighted mean diameter, D_m . Their comparisons showed that their agreement depends on the considered DSD variable. Specifically, the comparisons do quite well for reflectivity, rain rate and D_m , but they suggested that significant improvements in the satellite-based N_w retrievals is warranted.

Evaluation of particle size distributions from satellite measurements: Chase et al. (2020) investigated the current microphysical framework used in GPM/DPR precipitation retrievals with emphasis on snowfall estimates. Their analysis investigated the empirical relationship between rain rate R and mass-weighted mean diameter D_m . Their approach was to quantify the accuracy of the currently utilized relationship using surface observations in rainfall in different regions. Their analysis assessed the empirical relation prescribed between R and D_m . They then attempted to contextualize the changes needed in an R/D_m relationship in snowy regions. They used a large amount of surface data from GPM-sponsored field campaigns, as well as Department of Energy (DOE) measures obtained at several Atmospheric Radiation Measurement (ARM) sites and field campaigns. The principal conclusions from Chase et al. (2020) suggest the following: 1) assuming raindrops are spherical, comparisons between ground-based disdrometer measurements of rainfall show good agreement the current GPM/DPR retrievals; 2) classification of particle size distributions (PSD) by either stratiform or convective using the normalized intercept parameter (N_w) and the median volume diameter (D_0) improves comparisons; 3) ground-based comparisons of snowfall in Finland does not show consistency in the currently utilized $R-D_m$ relationship resulting in large GPM/DPR snowfall retrieval errors; and, 4) the variability in the mass of particles with a similar maximum dimension, i.e. density variability, likely causes poor correlation between R and D_m in snow.

CYGNSS and Geostationary Environmental Monitoring and Characterization

Mapping Flood Inundation: Flood detection and the generation of flood maps play essential roles in policymaking, planning, and implementing flood management options. Rajabi et al. (2020) use from CYGNSS to retrieve flood maps over regions affected by recent flood in the southeastern part of Iran. The study uses measurements over the Sistan and Baluchestan provinces during torrential rain in January 2020. This area has been at a high risk of flood in recent years and needs to be continuously monitored by means of timely observations. Flooded areas are detected based on a threshold test applied to the measured surface reflectivity. Images from Moderate-Resolution Imaging Spectroradiometer (MODIS) were used for evaluation of the results. The results successfully demonstrate that CYGNSS can produce short revisit time flood detection maps.

Detection and Mapping of Phytoplankton Outbreaks: A massive dust storm formed over the Sahara Desert in June 2020. The African dust cloud, which traveled over the tropical Atlantic's main development region for hurricanes, resulted in the highest aerosol optical

thickness (AOT) observed in the past two decades. Dust particles in the clouds are deposited on the ocean surface, impacting the ocean biogeochemistry through the supply of nutrients. Although there are remote sensing systems that can map the AOT, the locations of the aerosol particles deposited on the ocean surface remain unknown quantities with remote sensing measurements. In addition, the supplied nutrients are not static and are displaced by ocean currents. Nutrients trigger the phytoplankton (algae) blooms, which form a film on the ocean surface and affect the ocean surface tension. The change in ocean surface tension causes a local decrease of ocean surface roughness over the areas covered with phytoplankton. Rodriguez-Alvarez and Oudrhiri (2021) demonstrate that CYGNSS can detect changes in the ocean surface roughness, expressed as an increase in reflectivity when the surface becomes smoother. Decreased roughness due to a recent dust storm represents a key indicator of the presence of phytoplankton. The ability of CYGNSS to detect and map the presence of phytoplankton is demonstrated for the first time. Low ocean roughness signatures are observed in the Gulf of Mexico after the Sahara's dust storm circulation from Africa to the American continent from May to July 2020. CYGNSS data offer unprecedented spatial and temporal coverage that allows for the analysis of the signatures on time scales of 1-day, robust to the presence of clouds and dust clouds.

Using Machine Learning for Multi-Spectral Satellite Image Interpretation: Airborne dust has broad adverse effects on human activity, including aviation, human health, and agriculture. Remote sensing observations are used to detect dust and aerosols in the atmosphere using long established techniques. False color Red-Green-Blue (RGB) imagery using band differences sensitive to dust absorption (Dust RGB) is currently used operationally to assist forecasters and decision-makers in identifying dust at night and can aid process studies of dust events, but there are still limitations, subjectivity, and nuances to image interpretation making night-time dust identification difficult even for experts. This study applies machine learning to the problem of night-time dust detection with a simple random forest (RF) model using NASA/NOAA Geostationary Operational Environmental Satellite-16 (GOES-16) Advanced Baseline Imager (ABI) infrared imagery, band differences sensitive to dust absorption, and Dust RGB color components as inputs to the model. The RF-model described in Berndt et al. (2021) achieves an Area-Under-Curve (AUC) of 0.97 with a standard deviation of 0.04 for dust cases. For images with dust present, the model correctly labels 85% of dust pixels and 99.96% of no-dust pixels for all dust images in the validation data set. The addition of a single null case to the training data set drastically reduces error in labeling no-dust pixels as dust from 45% to 14.5%. Application of the machine learning model to the April 13–14, 2019 dust event demonstrates the ability of the model to identify dust during night-time hours when visual dust detection is limited by the cooling ground surface characteristics. In conjunction with developing the machine-learning model, the NASA Short-term Prediction Research and Transition Center (SPoRT) is partnering with NOAA National Weather Service forecast offices to evaluate the model for utility in weather forecasting operations. Preliminary evaluation has indicated 83% of the forecasters described the ML dust probabilities as having a High/Very High impact on their confidence to identify the dust plume compared to satellite imagery alone and false alarm signatures in the ML dust

probabilities were not an issue but an improvement beyond the typical false alarms in the Dust RGB at night.

Gridded Satellite Sounding Retrievals in Operational Weather Forecasting: The NASA Short-term Prediction Research and Transition Center (SPoRT) has been part of a collaborative effort within the National Oceanic and Atmospheric Administration (NOAA) Joint Polar Satellite System (JPSS) Proving Ground and Risk Reduction (PGRR) Program to develop gridded satellite sounding retrievals for the operational weather forecasting community (Berndt et al. 2020). The NOAA Unique Combined Atmospheric Processing System (NUCAPS) retrieves vertical profiles of temperature, water vapor, trace gases, and cloud properties derived from infrared and microwave sounder measurements. A new, optimized method for deriving NUCAPS level 2 horizontally and vertically gridded products is described here. This work represents the development of approaches to better synthesize remote sensing observations that ultimately increase the availability and usability of NUCAPS observations. This approach, known as “Gridded NUCAPS”, was developed to more effectively visualize NUCAPS observations to aid in the quick identification of thermodynamic spatial gradients. Gridded NUCAPS development was based on operations-to-research feedback and is now part of the operational National Weather Service display system. This paper discusses how Gridded NUCAPS was designed, how relevant atmospheric fields are derived, its operational application in pre-convective weather forecasting, and several emerging applications that expand the utility of NUCAPS for monitoring phenomena such as fire weather, the Saharan Air Layer, and stratospheric air intrusions.

Generating Proxy Water Surface Elevations in Preparation for the Surface Water Ocean Topography (SWOT) Mission: The Surface Water Ocean Topography (SWOT) mission will launch in early 2022 to provide the first global inventory of terrestrial surface water. Although SWOT is primarily a research mission with key science objectives in both the oceanography and hydrology domains, SWOT data are expected to have application potential to address many societal needs. For SWOT, and any unique satellite mission with a short lifetime, proxy data are essential in preparing to use new observations and maximizing mission impacts and societal benefits. Even after real SWOT data becomes available following launch, the need for proxy data will remain. There will still be value in generating proxy SWOT data for a broad range of activities, including simulated hydrology work and studies, software development, testing exercises, and education and outreach activities. SPoRT scientists tested two methods for deriving proxy SWOT water surface elevations (WSEs) from an Observing System Simulation Experiment (OSSE) using the Weather Research and Forecasting hydrological extension package (WRF-Hydro; Elmer et al. 2020). The first, a basic method, provides a simple and efficient way to sample WRF-Hydro output according to the SWOT orbit and add random white noise to simulate measurement error, like many previous approaches. An alternate method using the Centre National d'Etudes Spatiales (CNES) Large-Scale SWOT Hydrology Simulator accounts for additional sources of measurement error and produces output in formats comparable to that expected from official SWOT products. The basic method is ideal for river hydrology applications in which a full representation of SWOT measurement errors and spatial resolution is unnecessary, whereas the CNES simulator

approach is better-suited for more rigorous scientific studies that require a comprehensive error budget.

Investigating the Tropical Cyclone Diurnal Cycle to Improve Forecasts: SPoRT is using hyperspectral infrared satellite sounding retrievals to examine thermodynamic changes in the tropical cyclone (TC) environment associated with the diurnal cycle of radiation. Vertical profiles of temperature and moisture are retrieved from the Suomi National Polar-orbiting Partnership (S-NPP) satellite system, National Oceanic and Atmospheric Administration (NOAA)-20, and the Meteorological Operational (MetOp) A/B satellite system, leveraging both infrared and microwave sounding technologies. Vertical profiles are binned radially based on distance from the storm center and composited at 4-hr intervals to reveal the evolution of the diurnal cycle. For the three cases examined – Hurricane Dorian (2019), Hurricane Florence (2018) and Hurricane Irma (2017) – a marked diurnal signal is evident that extends through a deep layer of the troposphere. Statistically significant differences at the 95% level are observed in temperature, moisture, and lapse rate profiles, indicating a moistening and destabilization of the mid to upper troposphere that is more pronounced near the inner core of the TC at night. Observations support a favorable environment for the formation of deep convection caused by diurnal differences in radiative heating tendencies, which could explain why new diurnal pulses tend to form around sunset. These findings demonstrate that the diurnal cycle of radiation affects TC thermodynamics through a deep layer of the troposphere and suggest that hyperspectral infrared satellite sounding retrievals are valuable assets in detecting thermodynamic variations in TCs (Duran et al. 2021a).

Complementing Optical Remote Sensing with Synthetic Aperture Radar Observations of Hail Damage Swaths to Agricultural Crops in the Central United States: The normalized difference vegetation index (NDVI) has been frequently used to map hail damage to vegetation, especially in agricultural areas, but observations can be blocked by cloud cover during the growing season. In this study, the European Space Agency's Sentinel-1A/1B C-band synthetic aperture radar (SAR) imagery in co- and cross polarization is used to identify changes in backscatter of corn and soybeans damaged by hail during intense thunderstorm events in the early and late growing season. Following a June event, hail-damaged areas produced a lower mean backscatter when compared with surrounding, unaffected pixels [vertical-vertical (VV): -1.1 dB; vertical-horizontal (VH): -1.5 dB]. Later, another event in August produced an increase in co- and cross-polarized backscatter (VV: 0.7 dB; VH: 1.7 dB) that is hypothesized to result from the combined effects of crop growth, change in structure of damaged crops, and soil moisture conditions. Hail damage regions inferred from changes in backscatter were further assessed through coherence change detections to support changes in the structure of crops damaged within the hail swath. While studies using NDVI have routinely concluded a decrease in NDVI is associated with damage, the cause of change with respect to the damaged areas in SAR backscatter values is more complex. Influences of environmental variables, such as vegetation structure, vegetation maturity, and soil moisture conditions, need to be considered when interpreting SAR backscatter and will vary throughout the growing season.

Validation of Lidar Instruments

Lidars are uniquely capable of collecting high-precision and high spatiotemporal resolution observations that have been used for atmospheric process studies from the ground, aircraft, and space for many years. Two of the airborne lidars developed at NASA Langley Research Center are: (1) the coherent Doppler Aerosol WiNd (DAWN) lidar which measures vertical profiles of LOS velocity along selected azimuth angles that are combined to derive profiles of horizontal wind speed and direction (Bedka et. al., 2021); and 2) the High Altitude Lidar Observatory (HALO) which measures high resolution profiles of atmospheric water vapor (WV) and aerosol and cloud optical properties (Carroll et al., 2021). Over a 2-week period in April 2019 NASA conducted five research flights over the eastern Pacific Ocean with the DC-8 aircraft. The purposes included: (1) demonstrating DAWN and HALO measurement capabilities across a range of atmospheric conditions, (2) comparisons of DAWN and HALO measurements with the ESA Aeolus satellite backscatter and wind, and (3) ways in which atmospheric dynamic processes can be resolved and better understood through simultaneous observations of wind, water vapor, and aerosol profile observations.

Annual Performance Goal 1.1.9: NASA shall demonstrate progress in enhancing understanding of the interacting processes that control the behavior of the Earth system, and in utilizing the enhanced knowledge to improve predictive capability.

Section 1.1.9.1 Atmospheric Composition Focus Area

For demonstrating progress in enhancing understanding of the interacting processes that control the behavior of the Earth system, and in utilizing the enhanced knowledge to improve predictive capability, ACFA sponsored research in FY2021 to (a) improve our ability to retrieve aerosol and clouds and diagnose their properties and elucidate their interactions and impacts upon radiation; (b) more fully characterize spatial and temporal variability of pollution on regional scales; better understand the impacts of wildfires in particular; and through both to improvements in weather and air quality forecasts; (c) better describe the carbon cycle budget and improve our capability to model it; and (d) use both satellite observations and large-scale models to understand the chemical and physical processes that control the pace of ozone recovery, now and in the decades to come as well as the evolution and impacts of aerosols injected into the upper atmosphere. Finally, ACFA field missions buttressed satellite observations and modeling studies with observations to address a range of the issues mentioned above.

A. Aerosols, clouds & radiative forcing

The ACFA Radiation Sciences Program (RSP) and associated space-borne missions and sub-orbital projects, along with the Atmospheric Composition Modeling and Analysis Program (ACMAP), supported research in FY2021 on aerosol-cloud-radiation interactions, aerosol and cloud observations and modeling, and clouds, the water cycle and climate that relate to interacting processes and improving predictive capability. 16 significant papers in this topic area from the last year are summarized here.

Aerosol-cloud-radiation interactions

Obregón et al. (2021) used a novel methodology applied to CERES SYN 1-deg products for the period 2000–2019 to calculate the combined and individual effects of the aerosol optical thickness (AOT) and precipitable water vapor (PWV) on the solar radiation reaching the Earth’s surface. Spatial distributions of AOT and PWV effects, both individually and combined, show a close link with the spatial distributions of AOT and PWV themselves. The spatially averaged combined effect results in a –13.9% reduction in irradiance, while the average AOT effect is –2.3%, and the PWV effect is –12.1%. The study finds positive trends in AOT and PWV for 2000-2019. Consequently, significant negative trends are found for the effects. However, significant positive trends for the individual AOT and the combined AOT-PWV effects are found in specific regions, such as the eastern United States, Europe or Asia, indicating successful emissions control policies in these areas. This study contributes to a better understanding

of the individual and combined effects of aerosols and water vapor on solar radiation at a global scale.

[Chang et al. \(2021\)](#) examined spatio-temporal variations of above-cloud aerosol optical depth (ACAOD) and cloud optical depth (COD) using collocated aircraft and satellite measurements during the NASA EVS-2 ORACLES 2016 field experiment. ACAOD measurements from 4STAR and HSRL-2 are in satisfying agreement. Aerosol loadings in the southeast Atlantic commonly vary at sub-three-hourly temporal scale over spatial scales relevant to MODIS retrieval resolutions. The first evaluation of attenuation-corrected below-aerosol CODs from MODIS and SEVIRI against SSFR's COD retrievals (SSFR flew above the low-level cloud top and below the aerosol layer) was conducted by imposing temporal collocations of <15 and 15 – 60 minutes (<7.5 minutes for SEVIRI). Correcting the above-cloud AOD biases improves the agreement of COD retrievals between MODIS and SSFR, especially when imposing the tighter temporal collocation.

[Christensen et al. \(2020\)](#) used multiple years of hourly observations from the CERES Synoptic (SYN) product to study the formation and persistence of low-level clouds over 1×1 degree spatial domains. Lagrangian trajectories spanning several days along the classic stratus-to-cumulus transition zone are stratified by aerosol optical depth and meteorology. Clouds forming in relatively polluted trajectories tend to have lighter precipitation rates, longer average lifetime, and higher cloud albedo and cloud fraction compared with unpolluted trajectories. While liquid water path differences are found to be negligible, direct evidence is found of increased planetary albedo primarily through increased drop concentration (N_d) and cloud fraction, with the caveat that the aerosol influence on cloud fraction is positive only for stable atmospheric conditions. While the increase in cloud fraction can be large typically in the beginning of trajectories, the Twomey effect accounts for the bulk (roughly 3/4) of the total aerosol indirect radiative forcing estimate.

[Douglas and L'Ecuyer \(2020\)](#) utilized cloud and aerosol information from NASA's A-Train to estimate the net impact of aerosol-cloud interactions on Earth's energy balance as well as decompose this effect into components owing to separate contributions from cloud brightness and area. They found that cloud changes induced by anthropogenic aerosols increase cool the planet by 0.32 Wm^{-2} and that up to 1/5 of this effect stems from increases in cloud area.

As summarized in the IPCC AR6, recent changes to how clouds are represented in global models, especially over the Southern Ocean, resulted in a significant increase in climate warming. [Mülmenstadt et al. \(2021\)](#) demonstrated that tuning the model warm rain processes to CloudSat not only improves cloud representation but also leads to a greatly enhanced negative feedback, offsetting documented increases in model climate sensitivity. This increased negative feedback is associated with changing the lifetime of these Southern Ocean clouds and highlights how climate sensitivity associated with low cloud feedbacks is inescapably related to warm rain processes.

Aerosol and cloud properties are the primary determinants of the direct aerosol radiative effect (DARE). [Doherty et al. \(2021\)](#) estimated the combined impact of model aerosol and cloud biases on DARE using a first-order approximation and compared it to ORACLES measurement. Model improvements that reduce biases in only one property (e.g., single scatter albedo, but not cloud fraction) can increase DARE model biases even further. Model biases in aerosol extinction and in cloud fraction and optical depth contribute the largest biases in DARE, with aerosol single scatter albedo also making a significant contribution.

Deep convective clouds (DCCs) are important to global climate, atmospheric chemistry, and precipitation. In certain regions like the North Atlantic, dust is the dominant aerosol type; thus its microphysical effects on deep convective processes could be significant. [Zamora, L., and R. Kahn \(2020\)](#) developed a method using CloudSat data and MERRA-2 reanalysis products to quantify responses of DCC to dust and other aerosols in this region. They found that while dust is associated with increases in DCC prevalence by more than half, the association is driven more by the presence of marine aerosols. These observations suggest that not only is dust a comparatively ineffective CCN source, but it may also act as a condensation/coagulation sink for chemical precursors to CCN, reducing total CCN availability over large spatial scales by inhibiting new particle formation from marine emissions. These observations represent the first time this process, previously predicted by models, has been supported and quantified by measurements.

Aerosol and cloud observations and modeling

The western North Atlantic Ocean (WNAO) is a complex land-ocean-atmosphere system that experiences a broad range of atmospheric phenomena, which in turn drive unique aerosol transport pathways, cloud morphologies, and boundary layer variability. [Painemal et al. \(2021\)](#) provide the first comprehensive overview of the atmospheric circulation, boundary layer variability, three-dimensional cloud structure, and precipitation over the WNAO. Satellite data show a clear annual cycle in cloud droplet number concentration with maxima along the coast in winter and minima in summer, suggesting a marked annual cycle in aerosol-cloud interactions. Compared with satellite cloud retrievals, four climate models qualitatively reproduce the annual cycle in cloud cover and liquid water path, but with large discrepancies across models, especially in the extratropics.

Cloud drop number concentrations (N_d) over the western North Atlantic Ocean (WNAO) are generally highest during the winter (DJF) and lowest in summer (JJA), in contrast to aerosol proxy variables (aerosol optical depth, aerosol index, surface aerosol mass concentrations, surface cloud condensation nuclei - CCN] concentrations) that generally peak in spring (MAM) and JJA with minima in DJF. [Dadashazar et al. \(2021\)](#) used aircraft, satellite remote sensing, ground-based *in situ* measurements data as well as reanalysis data to characterize factors explaining the divergent seasonal cycles and furthermore probe into factors influencing N_d on seasonal time scales. The results can be summarized well by features most pronounced in DJF, including features associated with

cold air outbreak conditions such as enhanced values of CAO index, planetary boundary layer height, low-level liquid cloud fraction, and cloud-top height, in addition to winds aligned with continental outflow.

[Yu et al. \(2021\)](#) present a remote sensing and modeling assessment of the extraordinary West African dust transport event to the Caribbean. AERONET's wide distribution from the African source to the Caribbean sink affords the opportunity to assess and validate model and satellite optical, microphysical and radiative properties of transported dust.

[Meskhidze et al. \(2021\)](#) presented two new approaches for estimating atmospheric PM_{2.5} and chemical composition which are based on High Spectral Resolution Lidar (HSRL)-retrieved aerosol extinction values and types with Creating Aerosol Types from Chemistry (CATCH)-derived aerosol chemical composition. The first methodology (CMAQ-HSRL-CH) improves EPA's Community Multiscale Air Quality (CMAQ) predictions by applying variable scaling factors derived using remotely-sensed information about aerosol vertical distribution and types and the CATCH algorithm. The second methodology (HSRL-CH) does not require regional model runs and can provide atmospheric PM_{2.5} mass concentration and chemical speciation using only the remotely sensed data and the CATCH algorithm. Both methods led to considerable improvement in predicted PM_{2.5} concentrations. The HSRL-CH method will be able to make reliable estimates of PM_{2.5} concentration and chemical composition where HSRL data are available.

[Flower and Kahn \(2020\)](#) assessed multiple volcanic eruptions in Iceland (Eyjafjallajökull 2010, Grímsvötn 2011, and Holuhraun 2014–2015), using Multiangle Imaging Spectroradiometer (MISR) observations to infer information about the geological dynamics of each volcano and the properties and evolution of plume particles. With the MISR Research Algorithm (RA), they were able to distinguish sulfate/water-dominated volcanic plumes from Holuhraun and ash-dominated plumes from Eyjafjallajökull and Grímsvötn, and even identify subtler changes in ash particle size and light-absorption within plumes. Additionally, plume heights are retrieved geometrically from MISR. These are combined with surface thermal anomalies from the MODerate resolution Imaging Spectroradiometer (MODIS) and SO₂ concentrations derived from the Ozone Monitoring Instrument (OMI) to synthesize eruption remote-sensing chronologies. Their results illustrated the potential to distinguish qualitative differences in eruptive magma composition based on particle light absorption and plume profile from remote-sensing, demonstrating the enhanced capabilities of MISR and, more generally, remote-sensing analysis that can be applied globally, especially where suborbital volcano observations are limited or entirely absent.

Dust emission is initiated when surface wind velocities exceed the threshold of wind erosion. Therefore, accurate characterization of global distribution of the wind erosion threshold over different surface types is key in providing skillful simulations of dust climatology and seasonal cycles as well as dust forecasting. [Pu et al. \(2020\)](#) used the MODIS Deep Blue aerosol products to better constrain the parameterization of dust lifting mechanism from the source regions used in the aerosol models. These

improvements result in better performance of the aerosol models in predicting the timing of the dust outbreak.

[Ge et al. \(2021\)](#) analyzed two years of the Cloud-Aerosol Transport System (CATS) profile product and found that the amplitude of diurnal cycle is significantly correlated with the mean frequency of occurrence. High clouds and oceanic low clouds have a strong vertical development during nighttime, and continental low clouds tend to develop in daytime. These diurnal cycle of cloud (DCC) features can impact the strength and the direction of net cloud radiative forcing. Overall, large cloud cover and amplitude can amplify net cloud cooling effects, and high cloud nighttime (18:00 PM–06:00 AM) occurrence frequency can strengthen the cloud warming effects. To explain the DCC phenomenon, instantaneous links between cloud vertical structure and lower-tropospheric stability, vertical velocity and cold point temperature are discussed individually to show the evidence of their controls on cloud properties from tropics to midlatitude.

Clouds, the water cycle and climate

Understanding how tropical moisture, clouds, and precipitation co-vary is critical to understanding the response of the tropics to climate warming, but these relationships are uncertain in models and not well understood from an observational point of view.

[Höjgård-Olsen et al. \(2020\)](#) studied the co-variation of moisture, clouds, and precipitation in the tropics by combining cloud and precipitation observations from CALIOP and CloudSat with relative humidity profiles from the Megha-Tropiques satellite. They identify the meteorological conditions associated opaque cloud cover, low liquid water clouds and high ice clouds, characterizing for the first time these fundamental relationships using observations.

Low altitude Arctic clouds comprise most of the wintertime Arctic cloud cover and exert a substantial influence on the surface energy budget. Thus there is a potential for significant climate feedbacks between these clouds and sea ice. [Li et al. \(2020\)](#) examined the connection between wintertime Arctic leads, a source of moisture and turbulent flux exchanges between the warm ocean and the planetary boundary layer, and low-level clouds. With CALIOP observations of low-altitude cloud occurrence, they showed that across the Arctic fewer boundary layer clouds are found when leads occur more frequently. This counterintuitive result is attributed to a local feedback process between sea ice, the formation and re-freezing of leads, and boundary layer clouds. The net effect of this process is a negative climate feedback, where the lower occurrence of cloud provides a cooling effect as the frequency of leads increases in a warming Arctic.

B. Tropospheric composition, air quality and impacts of wildfires and COVID-19 shutdowns

ACFA research on the changing composition of the troposphere and the processes that impact air quality, particularly on regional scales, is chiefly supported by the Tropospheric Composition Program (TCP) together with a range of space-borne missions and sub-orbital projects and field programs. The research has included support

for a number of field campaigns to investigate the processes that control regional air quality as well as the maintenance of important observing systems at JPL's Table Mountain Facility and the AJAX aircraft at NASA Ames Research Center.

This section summarizes 19 papers from the last year spanning four topic areas: the interaction of physical, chemical and dynamical process that influence air quality, the effects of wildfires as revealed by the FIREX-AQ field campaign in 2019, temporal changes in regional air quality and public health impacts, and chemical processes in the background atmosphere.

Physical, chemical and dynamical processes contributing to air quality

Biomass burning emits 34-41 Tg yr⁻¹ of smoke aerosol to the atmosphere and directly influences the Earth's climate by attenuation of solar and terrestrial radiation. [Schill et al. \(2020\)](#) presented the first global-scale view of smoke aerosol in the atmosphere from the NASA Atmospheric Tomography Mission (ATom). They found that biomass burning particles in the remote troposphere are dilute but ubiquitous, with dilute smoke contributing as much as denser plumes to the associated aerosol scattering and absorption and climate impact. However, their measurements indicate that a high-resolution global aerosol model overestimates biomass burning aerosol mass in the remote troposphere by over 400%, largely due to insufficient wet removal by in-cloud precipitation.

[Buchholz et al. \(2020\)](#) analyzed a 16-year record (2002-2018) of CO from MOPITT and AOD from MODIS (both on the Terra satellite) and diagnosed the drivers of regional differences that could account for a slow-down in the declining CO trend. They found that CO declined faster in the first half (2002-2010) of the record compared to the second half (2010-2018), while AOD was more variable. They attributed a large first-half decline of CO over Northeast China to improvement in combustion efficiency, and a smaller decline in the 2nd half due to additional air quality improvements after 2010. The AOD records show that local changes in biomass burning are sufficiently strong to counteract the global downward trend in atmospheric CO, particularly in late summer.

Aircraft observations from the ORACLES deployments were used by [Pistone et al. \(2021\)](#) together with reanalyses to understand strongly linear correlation between pollution indicators (carbon monoxide and aerosol loading) and atmospheric water vapor content. This correlation is observed at all altitudes above the boundary layer and is shown to develop over the continent due to daytime convection within a deep continental boundary layer (up to ~5-6 km) and mixing with higher-altitude clean air. This work thus provides insights into the conditions and processes which cause water vapor to covary with plume strength, which has significant implications for separating meteorological from aerosol impacts of biomass burning aerosol on low clouds.

Major outcomes from the The Korea-United States Air Quality (KORUS-AQ) field study in 2016 are reported in [KORUS-AQ Special Issue of Elementa: Science of the Anthropocene](#) which represents a synthesis of major outcomes from the 2016 study. [Crawford et al., 2021](#) provide a comprehensive description of the field experiment and

the ground, airborne and satellite measurements that were made. They also include a high-level synthesis of the significant KORUS-AQ analyses and conclusions that have been published, as well as policy recommendations based on the findings of KORUS-AQ and that have been included in the Final Science Synthesis Report provided to South Korean policy makers. It serves as a peer-reviewed companion to the KORUS-AQ Final Science Synthesis Report also completed in the last year.

Recirculation of pollutants due to the bay breeze effect is a key meteorological mechanism impacting air quality near urban coastal areas, but regional and global chemical transport models have historically struggled to capture this phenomenon. [Dacic et al. \(2020\)](#) presented a case study of a high-ozone episode observed over the Chesapeake Bay during the NASA Ozone Water-Land Environmental Transition Study (OWLETS) in summer 2017 using GEOS-CF and MERRA2-GMI, two NASA global high-resolution coupled chemistry-meteorology models (CCMMs). In the case study, GEOS-CF was able to simulate surface level ozone diurnal cycles and vertical ozone profiles at small scales between the surface level and 2000 m ASL. Evaluating global chemical model simulations at sub-regional scales will help air quality scientists understand the complex processes occurring at small spatial and temporal scales within complex surface terrain changes, simulating nighttime chemistry and deposition.

[Chouza et al. \(2021\)](#) used the tropospheric ozone lidar at the JPL Table Mountain Facility (TMF) to investigate the impact of Los Angeles (LA) Basin pollution transport and stratospheric intrusions in the planetary boundary layer on the San Gabriel Mountains. The results of this study indicate a dominant role of the LA Basin pollution on days when high ozone levels were observed at TMF (March–October period). [Yates et al. \(2020\)](#) used airborne and ground-based measurements of ozone to highlight the impacts of pollution in California's San Joaquin Valley (SJV) on the Sierra Nevada Mountains, particularly at lower elevations. Ozone exposure across the range is linked to pollution in the SJV, affecting tree mortality and air quality. Ozone remains high overnight at the mountain sites, resulting in higher cumulative exposures to ozone than in the SJV, increasing the risk for damage to sensitive species like ponderosa pine.

[Eck et al. \(2020\)](#) analyzed AOD and PM_{2.5} during the May-June 2016 KORUS-AQ campaign. They found that the highest AOD and PM_{2.5} were associated with combined pollution transport from China plus significant cloud cover and/or sea fog. The particle volume was at least 10 times larger on high relative humidity (RH) pollution transport days due to humidification growth and/or cloud or fog processing of aerosol. The PM_{2.5} was significantly higher over central Seoul than at the coast during pollution transport events from China suggesting additional particle formation from gas-to-particle conversion over Seoul in the relatively large humidified particles with high water content.

Anthropogenic secondary organic aerosol (ASOA), formed from emissions of organic compounds, constitutes a substantial fraction of the mass of submicron aerosol in populated areas around the world and contributes to poor air quality and premature mortality. Precursor sources of ASOA are poorly understood, and there are large uncertainties in the health benefits that might accrue from reducing anthropogenic

organic emissions. [Nault et al. \(2021\)](#) showed that the production of ASOA in 11 urban areas on three continents is strongly correlated with the reactivity of specific anthropogenic volatile organic compounds. The differences in ASOA production across different cities can be explained by differences in the emissions of aromatics and intermediate- and semi-volatile organic compounds, indicating the importance of controlling these ASOA precursors. Using an improved model representation of ASOA driven by the observations, they attribute 340,000 PM2.5-related premature deaths per year to ASOA, which is over an order of magnitude higher than prior studies. A sensitivity case with a more recently proposed model for attributing mortality to PM2.5 (the Global Exposure Mortality Model) results in up to 900,000 deaths.

Trace constituents and wildfires: FIREX-AQ

The Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) airborne field study was conducted from July-September 2019. Analysis of observations is ongoing and expected to provide important advances in the understanding of fire emissions, chemistry and transport that promise to improve the application of satellite observations and models to forecast and quantify the impact of fire emissions on atmospheric composition, air quality, and Earth's radiation budget.

[Wiggins et al. \(2021\)](#) used the FIREX-AQ airborne observations to demonstrate the coupling between fire radiative power (FRP) observed from space and fire emissions of smoke tracers (CO₂, CO, and black carbon). With the availability of continuous FRP from the Geostationary Operational Environmental Satellite (GOES) Advanced Baseline Imager (ABI), these results demonstrate the potential for satellite observations to help better distribute total fire emissions over time in models. The improved timing of emissions is expected to influence model forecasts of smoke transport, chemistry, and downwind air quality impacts.

Temporal changes in regional air quality and impacts on public health

[Hammer et al. \(2020\)](#) reported global estimates of annual PM2.5 concentrations and trends for 1998–2018 using ensemble of satellite AODs, including DT, DB, MISR and MAIAC, GEOS-Chem chemical transport model, and ground-based monitoring. The consistent long-term satellite AOD and simulation enable trend assessment over a 21-year period, identifying significant downward trends for eastern North America ($-0.28 \pm 0.03 \mu\text{g m}^3 \text{yr}^{-1}$) and Europe ($-0.15 \pm 0.03 \mu\text{g m}^3 \text{yr}^{-1}$), upward trends for India ($1.13 \pm 0.15 \mu\text{g m}^3 \text{yr}^{-1}$) and for the globe ($0.04 \pm 0.02 \mu\text{g m}^3 \text{yr}^{-1}$). The contrast between the shorter-term positive trend of $2.44 \pm 0.44 \mu\text{g m}^3 \text{yr}^{-1}$ for India over 2005–2013 and the negative trend of $-3.37 \pm 0.38 \mu\text{g m}^3 \text{yr}^{-1}$ for China over 2011–2018 is remarkable, with implications for the health of billions of people.

Carbon monoxide (CO) is an atmospheric pollutant produced from combustion, such as wildfires and gasoline powered automobiles. [Hedelius et al. \(2021\)](#) used a 16-year satellite record to determine how atmospheric CO levels have been changing this century. Though sporadic, large wildfires happen somewhere every year which can affect trends

in CO. They found trends for small regions ($\sim 40 \times 40$ km) over the full 16 years and over 5-year subsets, and these vary significantly among regions and among the 5-year subsets. They then examine how CO levels in cities change compared to their surrounding region. In most cases, CO trends in cities do not vary significantly from trends in the surrounding region. In some regions where a decrease would be expected (like Los Angeles and Mexico City), large intra-annual variability was found.

[Wei, J., et al. \(2021\)](#) used the NASA MODIS MAIAC AOD to estimate PM_{2.5} concentrations over China using the Space-Time Extra-Trees (STET) model. The resulting PM_{2.5} dataset for China (China-High PM_{2.5}) provides the longest record (2000 to 2018) at a high spatial resolution of 1 km. The PM_{2.5} concentrations showed increasing trends till 2007, remained high until 2013, and declined thereafter following a series of government actions to combat air pollution in China. While nationwide PM_{2.5} concentrations have decreased by $0.89 \mu\text{g m}^3 \text{yr}^{-1}$ ($p < 0.001$) during the last two decades, the reduction has accelerated to $4.08 \mu\text{g m}^3 \text{yr}^{-1}$ ($p < 0.001$) over the last six years, indicating a significant improvement in air quality. Large improvements occurred in the Pearl and Yangtze River Deltas, while the most polluted region remained the North China Plain, especially in winter.

[Chen et al. \(2021\)](#) used Aura Ozone Monitoring Instrument (OMI) nitrogen dioxide (NO₂) and formaldehyde data to understand why surface ozone, a secondary pollutant, over China is still high despite the substantial reduction in air pollution emissions. They found that ozone-production efficiencies over much of the industrialized areas of China transitioned from being VOC-limited/transitional in the 2000s to transitional/NO_x-limited in the late 2010s because of China's NO_x emission controls, which were largely implemented beginning in 2013. VOC-limited conditions are known to suppress ozone when NO_x emissions, so increases in ozone were not surprising as NO_x emissions decreased initially in urban areas. As NO_x emissions continue to decrease further in China, the authors expect that ozone levels will begin decreasing more consistently across China. VOC emission controls in addition to NO_x emissions controls in urban areas (with VOC-limited or transitional conditions) would also likely lead to more rapid reductions in ozone in urban areas.

Organic aerosol (OA), with a large biogenic fraction in the summertime southeast US, adversely impacts air quality and human health. Stringent air quality controls have recently reduced anthropogenic pollutants including sulfate, but the impact on OA remains unclear. To examine this more closely, [Zheng et al. \(2020\)](#) examined three filter measurement networks for long-term constraints on the sensitivity of OA to changes in inorganic species, including sulfate and ammonia. They found that from 2000–2013, summertime OA decreased by $1.7\text{--}1.9 \text{ \% yr}^{-1}$ with little month-to-month variability, while sulfate declines rapidly with significant monthly difference in the early 2000s. In contrast, modeled OA from a chemical-transport model (GEOS-Chem) decreases by 4.9 \% yr^{-1} with much larger monthly variability, largely due to the predominant role of acid-catalyzed reactive uptake of epoxydiols (IEPOX) onto sulfate. This results suggests the needs to revisit IEPOX reactive uptake in current models.

[Demetillo et al. \(2020\)](#) used DISCOVER-AQ remote-sensing observations of nitrogen dioxide (NO₂) to explore the relationship between pollutant distributions and demographics for the Houston area. Combining NO₂ observations with data on income and ethnicity for the Houston area, they demonstrate the potential for using satellite observations to diagnose economic disparities in pollution exposure.

Chemical processes in the background atmosphere

Organic acids are important in aerosol growth and cloud nucleation and evolution. Formic acid is the largest component of organic acids in the troposphere and has been underestimated by models for some time. [Franco et al. \(2021\)](#) describe a new multiphase pathway for converting formaldehyde to formic acid in chamber experiments. An early paper pointing this out was published more than 10 years ago and affirmed that the issue was geographically widespread by several dispersed NDCC FTIR measurements as these are the only long-term measurements available. This work showed that this new pathway in chemistry climate models better reproduces NDACC formic acid observations.

Dimethyl sulfide (DMS), emitted from the oceans, is the most abundant biological source of sulfur to the marine atmosphere. Its oxidation products form secondary aerosols that affect Earth's radiative balance by scattering solar radiation and serving as cloud condensation nuclei. [Veres et al. \(2021\)](#) report the atmospheric discovery of a previously unquantified DMS oxidation product, hydroperoxymethyl thioformate (HPMTF, HOOCH₂SCHO), identified through global-scale ATom observations. The observations demonstrate that HPMTF is a major reservoir of marine sulfur. Observationally constrained model results show that more than 30% of oceanic DMS emitted to the atmosphere forms HPMTF, and there is a strong link between HPMTF and new particle formation and growth. These ATom observations have transformed our understanding of the global sulfur cycle.

Trends and variability in tropospheric hydroxyl (OH) radicals determine the lifetimes of many greenhouse gases, air pollutants, and ozone depleting substances. [Patra et al. \(2021\)](#) present new estimations of tropospheric OH trends and variability from 1985-2018 using global measurements from the AGAGE and NOAA networks of methyl chloroform (CH₃CCl₃), which reacts with OH, and a global chemistry transport model utilizing reanalysis meteorology. The inverse lifetime of CH₃CCl₃ (that is proportional to OH) shows significant year-to-year variations (~2%–3%), linked to global changes in OH sources and sinks, and that have a negative correlation with the El Niño Southern Oscillation.

C. Global carbon cycle processes and modeling

The Earth's carbon cycle is comprised of interactions among the atmosphere, land and ocean, and ACFA-supported space-borne and suborbital observations underpin efforts to understand these interactions and their contributions to evolution of the climate system. We summarize here two papers that focus on the changing balances in the carbon cycle

and the role of the biosphere and two papers that address our ability to model carbon emissions and fluxes.

[Liu et al. \(2021\)](#) provide Net Biospheric Exchange (NBE) estimates with quantified uncertainties for the 2010-2018 timeframe using OCO-2 data assimilated as primary observations. Continental- to regional-scale estimates of the component fluxes (gross primary productivity, biomass burning, and heterotrophic respiration) are also provided. This satellite-centric approach complements the Global Carbon Project (GCP) budget which is mostly based on *in situ* observations and modeling. This paper represents a major advance towards getting OCO-derived products to a larger user community.

Changes to the carbon sequestered in tropical forests and soils as a result of human activities and changes in rainfall, temperature, and CO₂ concentrations have a substantial impact on Earth's climate. [Worden et al. \(2021\)](#) summarized recent results that show that the tropical biosphere has changed significantly in the last two decades from the combined effects of climate variability and land use. For example, large areas of forest have been cleared in both wet and dry forests, increasing the source of carbon to the atmosphere. Concomitantly, tropical fire emissions had declined, at least until 2016, from changes in land-use practices and rainfall, increasing the net carbon sink. However, measurements of stocks, fluxes and inferred interactions between them do not point unambiguously to either positive or negative feedbacks in carbon and water exchanges. These ambiguities highlight the need for assimilation of these new measurements with Earth System models for a consistent assessment of process interactions, along with focused field campaigns that integrate ground, aircraft and satellite measurements, to quantify the controlling carbon and water processes and their feedback mechanisms.

[Chen et al. \(2020b\)](#) describe new techniques for predicting emissions from fires on the 1- to 6-month timescales often referred to as subseasonal to seasonal (S2S). Skill in environmental predictions on S2S timescales is highly desirable because of potential to support advance planning and mitigation, but the ability to predict phenomena such as fires and hazardous smoke events remains poorly understood. The modeling system developed for this work relies on both relationships between current and future fire season severity and linkages between climate variables and fires. Careful evaluation of predictions made for retrospective periods show that such models are capable of reproducing the spatial and temporal variability of fire emissions in many regions, which may lead to improved global fire and smoke forecasting systems in the future.

The ability to monitor and understand natural and anthropogenic variability in atmospheric carbon dioxide (CO₂) is a growing need for many scientists and policymakers around the world. While observations from satellites and ground-based sensors play a vital role in carbon monitoring, they are characterized by large gaps in coverage that complicate direct data analysis. In [Weir et al. \(2021\)](#) a novel method is presented for integrating satellite-based estimates of CO₂ flux with emissions inventories and surface CO₂ measurements that allows atmospheric models to produce high-quality estimates of atmospheric CO₂ concentrations in near real time. This work supports

NASA's ability to interpret satellite CO₂ observations and to predict short term CO₂ change in support of field campaigns.

D. Stratospheric composition change & ozone depletion

ACFA sponsors research under the Upper Atmosphere Research Program (UARP) as well as Atmospheric Composition Modeling and Analysis Program (ACMAP) that, for example, provides observations of ozone-depleting substances as well as UTLS aerosols that enable modeling and analysis of the processes that control the recovery of ozone and the evolution of aerosol particles in the UTLS and their potential impacts on both ozone and radiation. The latter includes research into the effects of smoke injections into the upper troposphere and lower stratosphere (UTLS) from pyroCbs as well as volcanoes. This section summarizes results for 8 papers in these two areas.

Chemistry and dynamics of upper atmosphere composition change

Springtime ozone depletion in the polar stratosphere is caused by chlorine and bromine species activated by low temperatures, with yearly loss in the Arctic much more variable than in Antarctica due to warmer temperatures and more disturbed stratospheric dynamics. Nevertheless, despite two decades of decreasing stratospheric chlorine and bromine through controls of the Montreal Protocol, very low ozone column levels were observed in the Arctic during 2020. To understand how this came about, [Feng et al. \(2021\)](#) used a three-dimensional atmospheric chemical transport model and satellite observations to show that the very low ozone values in the Arctic were a consequence of large chemical destruction and weaker-than-normal replenishment by transport, as was the case in the 2011.

Nitrous oxide (N₂O) is a long-lived greenhouse gas that drives climate change and ozone depletion, posing a threat to society's health and well-being. [Ruiz et al. \(2021\)](#) quantified the ability of multiple state-of-the-art atmospheric chemistry transport models to match the observed seasonal and multi-year fluctuations seen in both stratospheric N₂O observed by MLS and in surface N₂O observations. They found good agreement in the Northern Hemisphere, but inter-model disagreements and model/measurement disagreements in the Southern Hemisphere. They further showed that variability in Northern Hemisphere surface N₂O abundances is not driven by changes in emissions, as might be expected. Rather, the dominant contributor to surface N₂O variability is dynamically-driven changes in N₂O loss in the stratosphere and the subsequent transport of the N₂O-depleted air back into the troposphere.

Increases in upper tropospheric and lower stratospheric water vapor have been shown to lead to substantial surface warming. Thus the likely amplification of convective overshooting in a warming climate will result in a positive climate feedback mechanism. [Werner et al. \(2020\)](#) examined 15 years of lower stratospheric water vapor observations from Aura MLS, with a focus on the enhancements that result from overshooting deep convection, particularly over the North American summer monsoon. Enhanced abundances are indeed seen, ranging from 8 ppmv to as much as 26 ppmv, compared to

typical background values of 4-6 ppmv. By using co-located observations of cloud properties from the Aura MODIS sensor, they showed that the greatest enhancements in MLS-observed water vapor are associated with the measurements closest to the center of the largest convective systems.

Age of Air (AOA) is a powerful tool for measuring changes in transport in stratosphere transport and resulting impacts on the lifetimes of ozone and other trace species. [Strahan et al. \(2020\)](#) used long-term NDACC FTIR HCL and HNO₃ records to evaluate low frequency fluctuations and determine differences in age of air between the Northern and Southern Hemispheres. They showed that in the past 25 years the age of air in the SH has been decreasing by about 1 month per decade, evidence for asymmetries in hemispheric stratospheric dynamics that only be elucidated from long term observational datasets.

Evolution and impacts of aerosols in the lower stratosphere

The Australian New Year fires in January 2020 produced unprecedented injections of smoke and aerosol directly into the stratosphere, creating long-term effects comparable to a small volcanic eruption. This extraordinary stratospheric plume of fire emissions circled the globe twice while rising to ~35 km altitude over 110 days.

[Peterson et al. \(2021\)](#) used OMPS Nadir Mapper (NM) and Limb Profiler (LP) measurements to characterize the evolution and subsequent development of the smoke plumes. Shifts in stratospheric composition, radiative balance, and regional circulation are now seen as consequences of such events. The plume's detailed composition was examined by [Schwartz et al., GRL, 2020](#) who found that this smoke plume was characterized by unprecedented enhancements of MLS H₂O and biomass-burning products (CO, HCN, CH₃Cl, CH₃CN, and CH₃OH) accompanied by depressions in stratospheric species (O₃ and HNO₃). The densest part of the plume rose through the lower/middle stratosphere, with solar heating of smoke both driving the ascent and producing a ~1000 km wide anticyclonic vortex that served to confine the plume. This work builds on other papers also using MLS data (see *Kablick et al.* cited in last year's report) and examines the full range of MLS species impacted, using differences among these species to distinguish the various individual plumes resulting from discrete stratospheric injection events.

[Yu et al. \(2021\)](#) simulated the plume rise, transport, chemical, and climate impacts of the smoke and showed that the rise of the well into the stratosphere due to absorption of solar energy. Their results suggest that the smoke remained in the stratosphere for all of 2020 and that it measurably warmed the stratosphere by about 1–2 K for more than 6 months. The smoke had an impact on ozone as well; assuming similar heterogeneous reaction rates as sulfate aerosol, the smoke particles transported to high latitudes in the Southern Hemisphere should have produced about 4%–6% loss of the total column ozone at high southern latitudes.

Airborne measurements from the NASA Atmospheric Tomography Mission (ATom) have provided new insights into human impacts on the composition of far-flung regions of the global atmosphere. One of these potential impacts arises from the emission of SO₂ by commercial aviation. Using ATom measurements of the size distribution of particles with diameters > 3 nm, [Williamson et al. \(2021\)](#) found a mode of ultrafine stratospheric aerosol (smaller than 12 nm) in the lowermost stratosphere at mid- and high latitudes of the Northern Hemisphere that is largely absent in the Southern Hemisphere. This nanoscale mode was observed in all four seasons and furthermore was associated spatially with elevated SO₂, an important precursor for these nanoscale particles. They argue that commercial aircraft emissions are likely sources of this SO₂, and hence of these ultrafine particles. These nucleation mode particles have the potential to affect heterogeneous chemistry and aerosol–radiation interactions at global scale, adding a significant new factor to the recognized climatic impacts of aviation.

Section 1.1.9.2 Carbon Cycle and Ecosystems Focus Area

Contributions from the Carbon Cycle and Ecosystems Focus area to Annual Performance Indicator 1.1.9 included better constraining methane sources and sinks to reduce uncertainties, further improving the characterization of the ocean's biological pump to reduce uncertainties in climate predictions, and increasing humanity's understanding of anthropogenic impacts on landscapes and biodiversity.

Of interest across all Carbon Cycle and Ecosystems Focus area programs is the Surface Biology and Geology (SBG) mission, recommended by the 2017 Decadal Survey. SBG is anticipated to contribute significantly to improving the understanding of the Earth System, further elucidate the interconnections that exist between ecosystems, and facilitate new applications that target pressing societal priorities. Cawse-Nicholson et al. (2021) reviewed existing relevant algorithms and community-state-of-practice for SBG that span applications in snow/ice, aquatic environment, geology, and terrestrial vegetation, and highlighted the importance of SBG's high spatial resolution and spectral imagery to capture the hydrological, ecological, weather, climate, and solid earth dynamic states of the Earth's surface and quantify uncertainties.

Ocean Biology and Biogeochemistry

The biological carbon pump (BCP) is responsible for sequestering roughly 5-10 Pg of carbon per year. Small changes in the BCP can significantly alter the ocean's capacity to sequester carbon, which in turn impacts atmospheric CO₂ and climate. Improving the BCP's representation in Earth system models is essential to reduce uncertainties in climate predictions. Two recent studies, one in the North Atlantic and another in the Antarctic, have focused on better understanding key biological processes and reducing the uncertainty associated with parameterizing and modeling the seasonal phytoplankton phenology and bloom dynamics for those regions. Yang et al (2020) focused on the North Atlantic, leveraging bio-optical profiling floats' data to measure phytoplankton growth, division and loss rates, as well as the associated concentrations of chlorophyll-a and carbon. They compared these observations to an eddy-resolving ocean model, finding that the model lacked many features that have now been identified as key elements in phytoplankton phenology and revealing modeling areas where biases may be reduced in the simulated physical forcing, turbulent dynamics, and bio-physical interactions. Kim et al. (2021) conducted similar research to enhance our predictive understanding of the ocean carbon using numerical models to simulate time-evolving plankton dynamics during the growing season, particularly for the interfaces of land, ice, and water surrounding the West Antarctic Peninsula (WAP). Their data assimilation scheme used observations to constrain poorly understood processes, better partition primary production by phytoplankton groups, and piece together periodic observations from a variety of datasets that better explains the observed dynamics along the coastal WAP and reducing model misfit by 80% through improved model parameterizations.

In addition to better characterizing the BCP, researchers are studying how regional local ecosystems are being affected by climate forcings, such as temperature increases and

changes to the timing and rate of freshwater fluxes across the land-ocean interface. Bucci et al. (2020) predicted that higher temperatures and freshwater discharge in the Gulf of Maine, and particularly in the Bay of Fundy, will lead to earlier onset of harmful algal blooms of *Alexandrium catanella* by 1-2 months. This ecosystem shift is being triggered by one of the most rapidly warming parts of the ocean and has consequential impacts on the economy and human livelihood in this portion of New England, which is home to many important fishing and aquaculture activities. Studies like Bucci et al. (2020) help reduce the uncertainties in climate predictions and increase our understanding of the impacts of climate change on our ecosystems and the blue economy.

Terrestrial Ecology

Methane (CH₄) emissions from thawing permafrost amplify climate warming feedbacks. With an eye towards understanding atmospheric methane increases to achieve a better predictive capability of future changes, Lan et al. (2021) studied the drivers behind the global atmospheric CH₄ increase observed after 2006. The authors concluded that the dominant driver must be microbial emission increases, based on the isotopic signature of the methane observations. A significant decrease in hydroxyl radicals, the largest CH₄ sink, could not explain the post-2006 global CH₄ increase, and thus the authors suggested three potential drivers to these increases: i) increased emissions from microbial sources in the tropics, ii) moderate increases in fossil fuel emissions and decreases in biomass burning emissions, and iii) a significant decrease in soil sink accompanied by increases in wetland emissions. Further research into these potential drivers is warranted, but most importantly, ensuring that model set up and data assimilation techniques are used to further reduce uncertainties.

The atmospheric carbon dioxide seasonal-cycle amplitude (SCA), which describes the Northern Hemisphere rise and decline of CO₂ concentrations in autumn/winter and spring/summer, respectively, has been increasing. This is likely due to increases in gross primary production (GPP; the total amount of carbon take-up by plants through photosynthesis) relative to ecosystem respiration (ER); however, substantial uncertainty remains regarding the drivers of this SCA increase, largely because of the difficulty to quantify gross CO₂ fluxes and their sensitivity to climate change across large spatial extents. In a recent study, Hu et al. (2021) used a novel approach leveraging aircraft-based measurements of atmospheric carbonyl sulfide to provide estimates of GPP over the entire North American Arctic-Boreal Zone (ABR). They found that monthly GPP displayed different linear relationships with soil temperature in spring versus autumn. In spring to mid-summer, when GPP is most strongly correlated with soil temperature, their results suggested that warming-induced increases of GPP exceeded the increases in ER over the past four decades. In autumn, however, increases in ER were greater than GPP due to light limitations on GPP, thereby enhancing autumn net carbon emissions. Both effects have likely contributed to the atmospheric CO₂ SCA amplification observed in the ABR. These results help improve the understanding of interacting processes that control the behavior of the Earth system.

Land Cover/Land Use Change

New technological advances are enabling better ways to characterize human impact on the Earth System. One such impact is infrastructure. On-going and consistent building/structure mapping of physical constructions is crucial for urban science research and applications and for accurate estimations of fossil fuel CO₂ (FFCO₂) emission monitoring required for the successful implementation of the Paris Agreement within the United Nations Framework Convention on Climate Change (UNFCCC). One such method for characterizing urban infrastructure was presented by Mathews and Ngiem (2021), who examined methods to analyze three-dimensional urban built-up volume with lidar and radar data. Their chapter on Urban Remote Sensing presents a novel methodology and results for 3D building volume observations from satellite radar data with validation from 3D Lidar data in different environmental and climatic conditions at a high resolution (100m or better).

Improvement in greenhouse gas (GHG, including FFCO₂) measurement and monitoring is foundational to the control of global GHG emissions. Changes in land use have significant impacts on carbon emissions; having a good predictive understanding of these changes is critical to better constrain land use/change-induced carbon contributions. Slash-and-burn practices in forests and biomass burning are among the most important sources of greenhouse gas emissions and aerosols in South/Southeast Asia (S/SEA), and significantly impact other countries through transboundary air pollution. To capture science on this important practice for use in a variety of science and applications, a two-volume book on biomass burning in S/SEA was compiled and edited by Vadrevu et al. (2021) and published by CRC Press. The book includes contributions from 94 renowned scientists representing 18 countries including S/SEA, USA, and Europe. The book offers an interdisciplinary perspective on the mapping and monitoring of fires, impacts of biomass burning on the land resources, climate, and the atmosphere, including policy aspects. The chapters showcase examples of linking top-down remote sensing and bottom-up ground-based measurements with integrated modeling to quantify biomass burning and land-atmosphere interactions, with an eye towards improving predictive capabilities. This book will serve as a valuable guide for satellite remote sensing researchers studying fires, biomass burning, atmospheric science, ecology, spatial geography, remote sensing, and environmental science.

Biodiversity

Advances in modelling are critical to improve the predictive capability to detect changes in biological phenomena. For example, wildlife managers need reliable information on species distributions to make effective decisions regarding conservation of species. This has been traditionally done through species harvesting. However, Gilbert et al (2021) found that emerging citizen-science data streams can potentially supplement harvest-based monitoring by providing fine-resolution data that permit identification of species-environment relationships needed to predict occurrence and abundance. The authors combined into integrated species distribution models harvest records of six wildlife species with citizen-science camera-trap data in Wisconsin, USA, and concluded that such integrated models produced more precise species-environment relationships than using either dataset alone. This work demonstrates the utility of integrating datasets and the need for both to support wildlife management decisions.

Ensuring that the right models are applied to better understand species distribution and habitat utilization is important to guarantee robustness of results and the reliability of such predictive tools. Zuckerberg et al (2020) specifically addressed the issue of pseudoreplication when looking at scale-of-effect studies, which identify the spatial scale at which a species or population most strongly responds to habitat composition and configuration. Pseudoreplication can occur when sample sites are in close spatial proximity to one another and could violate the assumption of independence. Through a variety of simulations, the authors demonstrated that changing the amount of landscape overlap did not alter the degree of spatial autocorrelation. However, in their review of over 600 journal articles, they found that a third (29%) of the studies perceived overlapping landscapes as an issue requiring either changes in sampling design or statistical solutions. The concern over overlapping landscapes as a form of pseudoreplication acts as a potential red herring, detracting from more relevant concerns of proper sampling design and spatial autocorrelation in ecological studies.

Section 1.1.9.3 Climate Variability and Change Focus Area

Highlights of results published this past year related to the enhancement of the systems-level understanding and prediction of the Earth system relevant to the CVC FA are summarized below.

In 2009 NASA launched its Operation IceBridge. IceBridge's primary goal was to use airborne laser altimetry to bridge the gap in fine-resolution elevation measurements of ice from space between the conclusion of NASA's Ice, Cloud, and land Elevation Satellite (ICESat; 2003–2009) and its follow-on, ICESat-2 (launched 2018). Operation IceBridge (OIB) officially ended this year after a full year of overlap with ICESat-2. In addition to airborne lidars, the planes also carried additional instruments, such as radars and gravimeters. The combination of an expansive instrument suite and breadth of surveys enabled numerous fundamental advances in our understanding of the Earth's cryosphere. For land ice, OIB dramatically improved knowledge of interannual outlet-glacier variability, ice-sheet, and outlet-glacier thicknesses, snowfall rates on ice sheets, fjord and sub-ice-shelf bathymetry, and ice-sheet hydrology. Unanticipated discoveries included a reliable method for constraining the thickness within difficult-to-sound incised troughs beneath ice sheets, the extent of the firn aquifer within the Greenland Ice Sheet, the vulnerability of many Greenland and Antarctic outlet glaciers to ocean-driven melting at their grounding zones, and the dominance of surface-melt-driven mass loss of Alaskan glaciers. For sea ice, OIB significantly advanced our understanding of spatiotemporal variability in sea ice freeboard and its snow cover, especially through combined analysis of fine-resolution altimetry, visible imagery, and snow radar measurements of the overlying snow thickness. Such analyses led to the unanticipated discovery of an interdecadal decrease in snow thickness on Arctic sea ice and numerous opportunities to validate sea ice freeboards from satellite radar altimetry. While many of its data sets have yet to be fully explored, OIB's scientific legacy has already demonstrated the value of sustained investment in reliable airborne platforms, airborne instrument development, interagency and international collaboration, and open and rapid data access to advance our understanding of Earth's remote polar regions and their role in the Earth system (MacGregor et al., 2021).

Sea Ice in the Climate System

Precipitation is a major component of the hydrologic cycle and plays a significant role in the sea ice mass balance in the polar regions. Over the Southern Ocean, predicting precipitation is particularly uncertain due to the lack of direct observations in this remote and harsh environment. Boisvert et al. (2020) demonstrate that precipitation estimates from eight global model reanalyses produce similar spatial patterns between 2000 and 2010, although their annual means vary by about 250 millimeters per year, and there is little similarity in their representation of interannual variability. Rainfall and snowfall are partitioned in five reanalyses; snowfall suffers from the same issues as the total precipitation comparison, with all five reanalyses indicating similar spatial patterns, but differences in their magnitude. All reanalyses indicate precipitation on nearly every day of the year, with spurious values occurring on an average of about 60 days per year,

resulting in an accumulation of about 4.5 millimeters per year. While similarities in spatial patterns among the reanalyses suggest a convergence, the large spread in magnitudes points to issues with the background models in adequately reproducing precipitation rates, and the differences in the model physics employed. Further improvements to model physics are required to achieve confidence in precipitation rate, as well as the phase and frequency of precipitation in these products.

The timing of melt onset in the Arctic plays a key role in the evolution of sea ice throughout spring, summer and autumn. A major catalyst of early melt onset is increased downwelling longwave radiation, associated with increased levels of moisture in the atmosphere. Determining the atmospheric moisture pathways that are tied to increased downwelling longwave radiation and melt onset is therefore of keen interest. Horvat et al. (2021) employed a machine-learning technique known as Self Organizing Maps (SOM) on the daily sea level pressure for the period 1979–2018 over the Arctic during the melt season (April–July) and identified distinct circulation patterns. Melt onset dates were mapped on to these SOM patterns. The dominant moisture transport to much of the Arctic is enabled by a broad low pressure region stretching over Siberia and a high pressure over northern North America and Greenland. This configuration, which is reminiscent of the North American-Eurasian Arctic dipole pattern, funnels moisture from lower latitudes and through the Bering and Chukchi Seas. Other leading patterns are variations of this which transport moisture from North America and the Atlantic to the Central Arctic and Canadian Arctic Archipelago. Their analysis further indicates that most of the early and late melt onset timings in the Arctic are strongly related to the strong and weak emergence of these preferred circulation patterns, respectively.

Arctic Ocean surface circulation change should not be viewed as the strength of the anticyclonic Beaufort Gyre. While the Beaufort Gyre is a dominant feature of average Arctic Ocean surface circulation, empirical orthogonal function analysis of dynamic height (1950–89) and satellite altimetry–derived dynamic ocean topography (2004–19) by Morison et al. (2021) show the primary pattern of variability in its cyclonic mode is dominated by a depression of the sea surface and cyclonic surface circulation on the Russian side of the Arctic Ocean. Changes in surface circulation after Arctic Oscillation (AO) maxima in 1989 and 2007–08 and after an AO minimum in 2010 indicate the cyclonic mode is forced by the AO with a lag of about 1 year. Under increased AO, the cyclonic mode complex also includes increased export of sea ice and near-surface freshwater, a changed path of Eurasian runoff, a freshened Beaufort Sea, and weakened cold halocline layer that insulates sea ice from Atlantic water heat, an impact compounded by increased Atlantic Water inflow and cyclonic circulation at depth. The cyclonic mode's connection with the AO is important because the AO is a major global scale climate index predicted to increase with global warming.

Arctic sea ice is shifting from a year-round to a seasonal sea ice cover. This substantial transformation, via a reduction in Arctic sea ice extent and a thinning of its thickness, influences the amount of light entering the upper ocean. This in turn impacts under-ice algal growth and associated ecosystem dynamics. Field campaigns have provided valuable insights as to how snow and ice properties impact light penetration at fixed locations in the Arctic, but to understand the spatial variability in the under-ice light field there is a need to scale up to the pan-Arctic level. Combining information from satellites

with state-of-the-art model parameterizations is one means to achieve this. Stroeve et al. (2021) combine satellite and modeled data products to map under-ice light on a monthly time-scale from 2011 through 2018. Key limitations pertain to the availability of satellite-derived sea ice thickness, which for radar altimetry, is only available during the sea ice growth season. They showed that year-to-year variability in snow depth, along with the fraction of thin ice, plays a key role in how much light enters the Arctic Ocean. This is particularly significant in April, which in some regions, coincides with the beginning of the under-ice algal bloom, whereas we find that ice thickness is the main driver of under-ice light availability at the end of the melt season in October. The extension to the melt season due to a warmer Arctic means that snow accumulation has reduced, which is leading to positive trends in light transmission through snow.

Land Ice in the Climate System

A combination of airborne and ocean science data collection campaigns, as well as measurements taken by satellites, are critical tools for understanding remote parts of the cryosphere. Using data collected as a part of the Oceans Melting Greenland (OMG) airborne and ship-based campaigns, Wood et al. (2021) investigated how Atlantic Ocean water influenced retreat at 226 marine-terminating glaciers using ocean modeling, remote sensing, and in situ observations. They identified 74 glaciers in deep fjords with Atlantic Ocean water controlling 49% of the mass loss that retreated when warming increased undercutting by 48%. Conversely, 27 glaciers calving on shallow ridges and 24 in cold, shallow waters retreated little, contributing 15% of the loss, while 10 glaciers retreated substantially following the collapse of several ice shelves. The retreat mechanisms remain unknown at 87 glaciers without ocean and bathymetry data, which were responsible for 19% of the loss. Ultimately, they determined that ice sheet projections that exclude ocean-induced undercutting may underestimate mass loss by at least a factor of 2.

Despite the technologies available for ground-based data collection, satellites remain the only way in which we can collect sufficient data to improve projections and predictions of how the Earth's large bodies of ice will react to a changing climate. Using data collected by ICESat-2 over the West Antarctic Ice Sheet, Adusumilli et al. (2021) found large increases in height over the ice sheet in 2019. Using a computational model of the atmosphere and snow, they show that these height increases occurred due to increased snowfall. After evaluating the ability of the model to accurately represent ongoing changes, the model was used to show that more than 40% of height changes due to winter snowfall over West Antarctica occurred because regions in the atmosphere where abundant moisture is transported, called "atmospheric rivers", delivered large quantities of snow. ICESat-2 data allowed the team to accurately measure changes at the snow interface with near complete coverage over the entire continent four times a year at high along-track spatial resolution. This represents a major improvement over previous height change estimates from satellite radar altimetry, whose measurements represent changes occurring at an ambiguous interface within the firn column, or previous airborne and

spaceborne laser altimeters, which did not have sufficient spatial or temporal resolution for precise estimates of sub-annual height changes.

The land ice contribution to global mean sea level rise has not yet been predicted using ice sheet and glacier models for the latest set of socio-economic scenarios, nor using coordinated exploration of uncertainties arising from the various computer models involved. Two recent international projects generated a large suite of projections using multiple models, but primarily used previous-generation scenarios and climate models, and could not fully explore known uncertainties. Edwards et al. (2021) estimated probability distributions for these projections under the new scenarios using statistical emulation of the ice sheet and glacier models. They found that limiting global warming to 1.5 degrees Celsius would halve the land ice contribution to twenty-first-century sea level rise. The median decreases from 25 to 13 centimeters sea level equivalent (SLE) by 2100, with glaciers responsible for half the sea level contribution. The projected Antarctic contribution does not show a clear response to the "business as usual" emissions scenario, owing to uncertainties in the competing processes of increasing ice loss and snowfall accumulation in a warming climate. However, under pessimistic assumptions, Antarctic ice loss could potentially be five times higher, increasing the median land ice contribution to 42 centimeters SLE under "business as usual" policies and actions, with the 95th percentile projection exceeding half a meter even under 1.5 degrees Celsius warming. This would greatly hamper efforts to mitigate future coastal flooding caused by rising seas. Given this large range of SLE estimates, adaptation planning for twenty-first-century sea level rise must account for a factor-of-three uncertainty in the land ice contribution until climate policies and the Antarctic response are further constrained.

The future retreat rate for marine-based regions of the Antarctic Ice Sheet is one of the largest uncertainties in sea-level projections. The Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6) aims to improve projections and quantify uncertainties by running an ensemble of ice sheet models with atmosphere and ocean forcing derived from global climate models. Lipscomb et al. (2021) used the Community Ice Sheet Model (CISM) to run ISMIP6-based projections of ocean-forced Antarctic Ice Sheet changes. Using multiple combinations of sub-ice-shelf melt parameterizations and calibrations, the model was forced to run to steady state over many millennia. During the model experiments, basal friction parameters and basin-scale thermal forcing corrections are adjusted to optimize agreement with the observed ice thickness. The model is then run forward for 550 years, from 1950–2500, applying ocean thermal forcing anomalies from six climate models. In all simulations, the ocean forcing triggers long-term retreat of the West Antarctic Ice Sheet, especially in the Filchner–Ronne and Ross sectors. Mass loss accelerates late in the 21st century and then rises steadily for several centuries without leveling off. The resulting ocean-forced sea-level rise at year 2500 varies from about 150 to 1300 millimeters, depending on the melt scheme and ocean forcing. However, large uncertainties remain, as a result of parameterized sub-shelf melt rates, simplified treatments of calving and basal friction, and the lack of ice–ocean coupling.

Oceans in the Climate System

One of the scientific thrusts of the Physical Oceanography and CVC area is to improve our understanding and prediction of the large-scale ocean energy, heat, and water cycle budgets on time scales of seasons to decades by combining ocean observations within a theoretical framework.

Estimating the Circulation and Climate of the Oceans

With certain similarities with numerical weather forecasting, there are subtle but important considerations in ocean state estimation, namely conservation of basic physical properties such as heat, salt, or momentum, that require alternative data assimilation approaches. While budget closure is of little importance for weather forecasts, as their violation has no impact on short-range prediction skill, budget closure and thus absence of discontinuity in the analysis time when the model is forced toward the data, is crucial to the understanding of climate change and ocean's role in climate. NASA supports production of a robust estimate and evolution of ocean state over the past few decades through development of the Estimating the Circulation and Climate of the Ocean (ECCO) framework (*ECCO Consortium et al., 2021*). The framework 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. Today, ECCO supports a wide range of applications in climate research, including ocean circulation and transport, ocean heat and freshwater budgets, ocean-ice coupling, sea level rise, air-sea interaction, ocean water cycle, carbon cycle and biogeochemical changes. For a full list of thousands of publications see <https://ecco-group.org/>.

To accelerate NASA's open science evolution, this year the ECCO team implemented novel analytical capabilities on the cloud, expanding usability and transparency of NASA data assets in climate research. This is an important milestone for the agency and climate community being the first successful NASA's cloud-native climate modeling effort. By lending itself to open science, ECCO is growing its user community, widening the range of its science applications, enabling collaboration, and solving big-data issues when needing to compute Petabytes of data at once (*Abernathy et al., 2021; Gentemann et al., 2021*).

Ocean predictions and projections of sea level rise

As a centralized sea level effort, NASA leads a multi-disciplinary collaboration among ocean physicists, cryospheric scientists, geodesists, and hydrologists through the NASA Sea Level Change Team (N-SLCT; <https://sealevel.nasa.gov>). One of the science goals of N-SLCT is to improve sea level projections on multiple time horizons and deliver NASA's latest knowledge to the public and decision-makers. A major milestone of N-SLCT this year is delivering the location-based sea level projections produced by the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report. The tool

allows users to view emission-scenario dependent global and regional sea level projections from 2020 to 2150. This is a first data-delivery partnership between IPCC and NASA (or any Federal agency), anticipated to become a "game-changer" for making IPCC sea level projections openly-accessible to the international community, stakeholders, Federal partners, and sea level practitioners across the world.

Prediction of tides and tidally-forced motions is one of longest application of dynamical theory, dating back to early work by Laplace (1775) of what is now known as the shallow-water equations to new classes of models that predict ocean response to tidal and atmospheric forcing and resolve arich spectrum of tides and internal gravity waves (see, e.g., *Arbic et al. (2018)*). In particular, prediction of tides of amplified magnitudes, or high tides, has gained renowned interest due to their linkage to the increased occurrence and severity of local flood events in coastal areas around the United States. The increase in high-tide flooding has been attributed to both global warming tendencies, sea level rise, as well as inter-annual, decadal and longer ocean fluctuations. A new N-SLCT study by *Thompson et al. (2021)* examines the impact of the long-period tides and predicts that a conjunction of tidal and ocean patterns, plus rising sea levels, will lead to a large increase in the frequency of high-tide flooding for a number of U.S.coastal areas in the 2030s and beyond. In the mid-2030s, every U.S. coast will experience rapidly increasing high-tide floods, when a lunar cycle will amplify rising sea levels caused by climate change. An 18.6-year cycle in the Moon's orbit means that in the 2030 the Moon will start exerting greater pull on ocean tides, setting off the increase in the frequency of high-tide flooding in multiple US coastal cities, particularly for the Atlantic and Gulf Coast regions.

Another active area of research in ocean prediction is related to air-sea coupling and ocean's role in improving predictions of storm and hurricane dynamics. Observing ocean extremes, such as marine heat waves, is critical information for forecasting landfall storm intensification (*Dzwonkowski et al., 2020*). To further improve predictive capabilities of hurricane dynamics, a number of improvements were made this year to wind and precipitation data that are routinely used by hurricane forecasts (*Wentz et al., 2021; Manaster et al., 2021; Meissner et al., 2021*). *Stow et al. (2020)* looked at various radar frequencies used to measure wind speed by NOAA aircraft and NASA satellites to see how each performs. This provides better understanding of sources of error, helps with planning future instruments and missions, and improves our predictive capabilities of tropical storms and high-wind events.

The Integrated Earth System & Modeling

Results from studies utilizing CVC-supported Earth system models aimed at improving the understanding of the interacting Earth system and Earth system prediction included:

Climate modeling advances

Miller et al. [2021] describe simulations of the CMIP6 historical period 1850–2014, characterized by the emergence of anthropogenic climate drivers like greenhouse gases, for several configurations of the NASA Goddard Institute for Space Studies (GISS) Earth

System Model E2.1. The GISS-E2.1 ensembles are more sensitive to greenhouse gas forcing than their CMIP5 predecessors (GISS-E2) but warm less during recent decades due to a forcing reduction that is attributed to greater longwave opacity in the GISS-E2.1 pre-industrial simulations. This results in an atmosphere less sensitive to increases in opacity from rising greenhouse gas concentrations, demonstrating the importance of the base climatology to forcing and forced climate trends. Most model versions match observed temperature trends since 1979 from the ocean to the stratosphere. The choice of ocean model is important to the transient climate response - as found previously in CMIP5 GISS-E2, more efficient export of heat to the deep ocean results in a smaller rise in tropospheric temperature. Model sea level rise over this period results from drawdown of aquifers to meet irrigation demand, along with a smaller contribution from thermal expansion. This shows how fully coupled models can provide indirect observational constraints upon forcing, in this case, constraining irrigation rates with observed sea level changes.

Atmospheric rivers (ARs) - narrow plumes of strong water vapor transport - are responsible for much of the precipitation along the West Coast of the United States. The most intense precipitation events there are almost always induced by an AR on the coast of Oregon and Washington and can result in detrimental impacts on society due to mudslides and flooding. To accurately predict AR events on numerical weather prediction, subseasonal, and seasonal time scales, it is important to understand the large-scale impacts on extreme AR events. Collow et al. [2021] compare characteristics of ARs that result in an extreme precipitation to more typical ARs on the coast of Washington State. In addition to more intense water vapor transport, notable differences in the synoptic forcing are present during extreme precipitation events that are not present during typical AR events. Subseasonal and seasonal teleconnection patterns are known to influence the weather in the Pacific Northwest and are also investigated. The Madden-Julian oscillation (MJO) plays a role in determining the strength of precipitation associated with an AR on the Washington coast. Phase 5 of the MJO (convection centered over the Maritime Continent) is the most common phase during an extreme precipitation event, while phase 2 (convection over the Indian Ocean) discourages an extreme event from occurring. Interactions between El Niño-Southern Oscillation (ENSO) and the propagation speed of the MJO result in extreme events during phase 1 of the MJO and El Niño but phase 8 during neutral ENSO conditions.

The movement of tropical cyclones (TCs), particularly around the time of landfall, can substantially affect the resulting damage. Recently, trends in TC translation speed and the likelihood of stalled TCs such as Harvey have received significant attention, but findings have remained inconclusive. Hassanzadeh et al. [2020] examine how the June-September steering wind and translation speed of landfalling Texas TCs change in the future under anthropogenic climate change. Using several large-ensemble/multi-model datasets, they find pronounced regional variations in the meridional steering wind response over North America, but—consistently across models—stronger June-September-averaged northward steering winds over Texas. A cluster analysis of daily wind patterns shows more frequent circulation regimes that steer landfalling TCs northward in the future. Downscaling experiments show a 10-percentage-point shift from the slow-moving to the

fast-moving end of the translation-speed distribution in the future. Together, these analyses indicate increases in the likelihood of faster-moving landfalling Texas TCs in the late 21st century.

Droughts that span the states of Washington, Oregon, and California are rare but devastating due to their large spatial coverage and potential loss of redundancies in water, agricultural, and fire-fighting resources. Such pan-coastal droughts require a more precise understanding of the roles played by the Pacific Ocean and internal atmospheric variability. Baek et al. [2021] employ 16-member ensembles of the Community Atmosphere Model version 5 and Community Climate Model version 3 forced with observed sea surface temperatures (SSTs) from 1856 to 2012 to separate and quantify the influences of the tropical Pacific and internal atmospheric variability on pan-coastal droughts; all other boundary conditions are kept at climatological levels to explicitly isolate for the impacts of SST changes. Internal atmospheric variability is the dominant driver of pan-coastal droughts, accounting for 84% of their severity, and can reliably generate pan-coastal droughts even when ocean conditions do not favor drought. Cold phases of the Pacific Ocean play a secondary role and contribute, on average, only 16% to pan-coastal drought severity. Spatiotemporal analyses of precipitation and soil moisture along the U.S. Pacific coast corroborate these findings and identify an antiphased wet–dry dipole pattern induced by the Pacific to play a more secondary role. The model framework expands on previous observational analyses that point to the spatially uniform forcing of internal atmospheric variability as the more dominant mode of hydroclimate variability along the U.S. Pacific coast. The secondary nature of oceanic forcing suggests limited predictability of pan-continental droughts.

Ren et al. [2021] conduct an intercomparison of the column-integrated moist static energy (MSE) and water vapor budget of the Madden–Julian oscillation (MJO) among six modern global reanalysis products (RAs). Inter-RA differences in the mean MSE, MJO MSE anomalies, individual MSE budget terms, and their relative contributions to the propagation and maintenance of MJO MSE anomalies are examined. Also investigated is the relationship between the MJO column water vapor (CWV) budget residuals with the other CWV budget terms as well as with the two parameters that characterize cloud–radiation feedback and moisture–convection coupling. Results show a noticeable inter-RA spread in the mean-state MSE, especially its vertical structure. In all RAs, horizontal MSE advection dominates the propagation of the MJO MSE while column-integrated longwave radiative heating and vertical MSE advection are found to be the key processes for MJO maintenance. The MSE budget terms directly affected by the model parameterization schemes exhibit high uncertainty. The differences in anomalous vertical velocity mainly contribute to the large differences in vertical MSE advection among the RAs. The budget residuals show large inter-RA differences and have nonnegligible contributions to MJO maintenance and propagation in most RAs. RAs that underestimate (overestimate) the strength of cloud–radiation feedback and the convective moisture adjustment time scale tend to have positive (negative) MJO CWV budget residual, indicating the critical role of these processes in the maintenance of MJO CWV anomalies. These results emphasize that a correct representation of the interactions

among moisture, convection, cloud, and radiation is the key for an accurate depiction of the MJO MSE and CWV budget in RAs.

Swenson and Straus [2021] introduced an experimental technique for controlling atmospheric diabatic heating in the fully-coupled NCEP Climate Forecast System version 2 climate model, to investigate the role of tropical forcing in the Indian summer monsoon and its contribution to global seasonal prediction skill. The ‘added heating’ mechanistic approach they used does not interfere with any internal model feedbacks. The approach was used to correct bias in the three-dimensional tropical heating over the Indo-Pacific. The June through September seasonal mean, trend and parabolic fit in diabatic heating are corrected for each year separately over a 20-year set of seasonal re-forecasts, resulting in a 60–90% reduction in the mean-squared error of Indo-Pacific heating from an initial set of control re-forecasts, two-thirds of which is associated with the climatological bias. This resulted in higher skill in the climatological mean and inter-annual variability of local low-level winds and the underlying sea surface temperature (SST). Improvements are most significant over the equatorial Indian Ocean with a removal of the climatological low-level westerly bias and SST gradient bias along with substantially more skill in inter-annual variability. Although there is very little improvement in the model rainfall over India, there is improvement in the low-level circulation. The lack of significant improvement in rainfall prediction may be partly related to the representation of convection and/or the coarse resolution grid of the model.

Cryospheric modeling advances

Current mass loss on the Greenland Ice Sheet (GrIS) includes a significant contribution from surface runoff. The circumstances associated with melt events are important for understanding the global sea level contribution of the GrIS. In late July 2019, surface melt occurred over 62% of the GrIS, including Summit Station. The general circulation leading to the event is found to be dissimilar to 2012 and other events documented in the 21st century, with warm air associated with remote atmospheric blocking over western Europe eventually transiting west to the GrIS. Gravimetric data indicate that the 2019 summer mass loss was 137 Gt more than the 2004–2010 median, or about 92% of the 2012 record. Mass loss during the event was significant in GrIS northeastern regions in 2019. As compared to 2012, the southwest did not fully participate. Similar circulation patterns have not previously been associated with significant melt.

Understanding the role of atmospheric circulation anomalies on the surface mass balance of the Greenland ice sheet (GrIS) is fundamental for improving estimates of its current and future contributions to sea level rise. Tedesco and Fettweis [2020] use a combination of remote sensing observations, regional climate model outputs, reanalysis data, and artificial neural networks to show that unprecedented atmospheric conditions occurring in the summer of 2019 over Greenland promoted new record or close-to-record values of surface mass balance (SMB), runoff, and snowfall. Runoff in 2019 ranked second within the 1948–2019 period (after 2012) and first in terms of surface mass balance negative anomaly for the hydrological year 1 September 2018–31 August 2019. The summer of

2019 was characterized by an exceptional persistence of anticyclonic conditions that, in conjunction with low albedo associated with reduced snowfall in summer, enhanced the melt–albedo feedback by promoting the absorption of solar radiation and favored advection of warm, moist air along the western portion of the ice sheet towards the north, where the surface melt has been the highest since 1948. The analysis of the frequency of daily 500 hPa geopotential heights obtained from artificial neural networks shows that the total number of days with the five most frequent atmospheric patterns that characterized the summer of 2019 was 5 standard deviations above the 1981–2010 mean, confirming the exceptional nature of the 2019 season over Greenland.

Chemistry/climate modeling advances

Biomass burning emits ~34–41 Tg yr⁻¹ of smoke aerosol to the atmosphere. Biomass burning aerosol directly influences the Earth’s climate by attenuation of solar and terrestrial radiation; however, its abundance and distribution on a global scale are poorly constrained, particularly after plumes dilute into the background remote troposphere and are subject to removal by clouds and precipitation. Schill et al. [2020] report global-scale, airborne measurements of biomass burning aerosol in the remote troposphere taken during four series of seasonal flights over the Pacific and Atlantic Ocean basins, each with near pole-to-pole latitude coverage. Biomass burning particles in the remote troposphere were dilute but ubiquitous, accounting for one-quarter of the accumulation-mode aerosol number and one-fifth of the aerosol mass. In comparison with a high-resolution global aerosol model, the model overestimated biomass burning aerosol mass in the remote troposphere with a mean bias of >400%, largely due to insufficient wet removal by in-cloud precipitation. Updating the model’s aerosol removal scheme to improve agreement with the observations showed that on the global scale, dilute smoke contributes as much as denser plumes to biomass burning’s scattering and absorption effects on the Earth’s radiation field.

Climate prediction advances

Lim et al. [2020] examined the within-season monthly variation of the El Niño response over North America during December—March using the NASA/GEOS model. As with previous studies, the skill of 1-month-lead GEOS coupled model forecasts of precipitation over North America is largest for February and smallest for January, with similar results in an uncoupled mode. A key finding is that the relatively poor January skill is the result of the model placing the main circulation anomaly over the northeast Pacific - slightly to the west of the observed anomaly. This results in precipitation anomalies that lie off the coast instead of over land as observed. During February the observed circulation anomaly over the northeast Pacific shifts westward, lining up with the predicted anomaly, which is essentially unchanged from January, resulting in both the observed and predicted precipitation anomalies remaining off the coast. Furthermore, the largest precipitation anomalies occur along the southern tier of states associated with an eastward extended jet—something that the models capture reasonably well. Simulations with a stationary wave model indicate that the placement of January El Niño response to

the west of the observed over the northeast Pacific is the result of biases in the January climatological stationary waves, rather than errors in the tropical Pacific El Niño heating anomalies in January. Furthermore, the relatively poor simulation of the observed January climatology, characterized by a strengthened North Pacific jet and enhanced ridge over western North America, can be traced back to biases in the January climatology heating over the Tibet region and the tropical western Pacific.

Ito et al. [2020] examined NASA GISS ModelE2.1-G-CC Earth System Model coupled climate-carbon cycle simulations that were submitted to the sixth Coupled Model Intercomparison Project (CMIP6) Coupled Climate-Carbon Cycle MIP (C4MIP). Atmospheric CO₂ concentrations and carbon budgets for the land and ocean in historical simulations were generally consistent with observations, although some issues were found with excess uptake from prescribed land cover change, high Leaf Area Index values, and an insufficient net carbon land sink. The global ocean carbon uptake agreed well with the observations. Future climate projection at 2091-2100 show a northward shift of temperate deciduous forest climate and expansion across Eurasia along 60 °N latitude, and dramatic regional biome shifts from drying and warming in continental Europe. For this model, variation of land feedback parameters arises from fertilization feedback being less sensitive due to lack of increased vegetation growth, and the comparably more negative ocean carbon-climate feedback is due to the large slowdown of the Atlantic overturning circulation.

Lerner et al. [2021] also investigated the carbon cycle, specifically looking at drivers of air-sea CO₂ flux seasonality and long-term changes. The paper finds that in the GISS-E2.1-G model, the seasonal cycles of the CO₂ flux and NPP have improved, although there is large regional variability in the improvement. The model produces similar modeled and observed CO₂ flux seasonal cycles in the subtropical gyres and in the Southern Ocean. Biases in seasonal cycles are largest in the subpolar and equatorial regions, resulting from a combination of biases in temperature, DIC, alkalinity, and wind speed. In simulations with elevated atmospheric CO₂ levels, the paper notes increases in seasonal amplitudes of both air-sea fluxes of CO₂ and surface concentrations. This results from an increase in the sensitivity of seawater CO₂ to its drivers in the elevated CO₂ simulation.

Section 1.1.9.4 Earth Surface and Interior Focus Area

NASA's Earth Surface and Interior focus area (ESI) supports research aimed at characterizing the dynamics of the solid Earth, improving the capability to assess and respond to natural hazards and extreme events. Building on the body of work under 1.1.8 "characterizing the behavior of the Earth system," ESI studies seek to improve understanding of the interacting processes that "control the behavior of the Earth system" and hence "improve predictive capability" as described under performance goal 1.1.9. Improving predictive capability in ESI centers on working towards probabilistic forecasting, since the prediction of place, time, and intensity of an event in the solid-Earth system is generally not yet possible. ESI predictive capabilities may also address other long-term transient processes such as ongoing vertical land motion associated with fluid injection or withdrawal, volcanic unrest, soil compaction, and other near- or subsurface processes. With this in mind, studies that inform, or develop capabilities to help inform the occurrence of future events or the effects they may have on a larger system are classified under 1.1.9.

Geohazards

One of the strengths of ESI relates to analyzing and modeling datasets derived from various remote sensing techniques to forecast the likelihood of geohazards. The societal benefits of these findings are significant as they reduce the risk on the life and livelihood of people that may be affected by these hazards. This year, geohazard forecasting techniques have been employed to address three types of hazards: earthquakes, volcanoes, and landslides.

Earthquakes

Identifying the methods for monitoring and measuring earthquakes and the seismic cycle are useful in mitigating and forecasting future events. In the past year, several researchers have made developments in understanding some of the processes that govern the occurrence rate and magnitude of earthquakes, improving our forecasting abilities.

Ward et al. (2021) examined the relationship between rheologic variations in the crust and the rate at which seismic moment accumulates along the San Andreas fault system. Using both GNSS and InSAR data they constrain surface deformation rates of a four-dimensional viscoelastic deformation model that incorporates rheological variations. They found that the change in earthquake potential scales almost linearly with plate thickness variations surrounding the fault, suggesting that variations in crustal rheology have an important impact on earthquake magnitude forecasts.

Dutilleul et al. (2020) examined the periodicity patterns of earthquakes in northern and central California to calculate the likelihood of earthquake hypocenter depths and the number of monthly earthquakes. They used stochastic declustering to produce a 2-D and 3-D hypocenter point pattern observed over a region and months, years or decades. A semiannual periodicity was detected in both the original catalog in the region and the 2-D

declustered catalogs of hypocenter depth which was fitted with the goal of relating this to periodicities found in the time series of monthly earthquake numbers. Dutilleul et al. (2021) revisited using periodicity to forecast earthquake occurrence and hypocenter depth near Parkfield, California by examining its relationship with annual hydrological, atmospheric, thermal, and tidal loadings. They found that earthquakes exhibit different periodicities in monthly numbers over 1994–2002 and 2006–2014, indicating a changed distribution of earthquake occurrence within the year after 2003–2005, which may be caused by a weakened Spring peak of pore pressure or altered permeability conditions due to the recent mainshocks.

Volcanoes

Understanding the processes that lead to an eruption help researchers to better forecast when the next volcanic eruption might occur. Some closed volcanic systems have deformation that can emerge or intensify weeks to months before a volcanic eruption whereas open systems are more dependent on changes in thermal and gas output or composition.

Girona et al. (Nature, 2021) examines how volcanogenic surface heat emissions relate to pre-eruptive processes and vary before eruption. They performed a statistical analysis of TIR measured emission before five different volcanoes and found significant long-term (years), large-scale (tens of square kilometers) increases in their radiant heat flux at volcanic edifices. They attribute large-scale thermal unrest to the enhancement of underground hydrothermal activity and suggest that such analysis of satellite-based infrared observations can improve constraints on the thermal budget of volcanoes, early detection of pre-eruptive conditions and assessments of volcanic alert levels.

Roman and Lundgren (Nature, 2021) studied how caldera collapse can act as the driving factor for large effusive eruptions. They provide a physical model, which is consistent with data from the 2018 Kīlauea eruption, which accounts for both the quasi-periodic stick–slip collapse of the caldera roof and the long-term eruptive behavior of the volcano. The model demonstrates that it is the caldera collapse itself that sustains large effusive eruptions, and that triggering caldera collapse requires topography-generated pressures. They also determined that this physical framework is generally applicable to the largest instrumented caldera collapse eruptions of the past fifty years.

Landslides

Although landslides rarely claim lives, they can cause structural damage and can fail rapidly, transitioning into fast moving landslides. Several environmental factors including precipitation, topography, and flow composition can influence the stability of a landslide and can be used to forecast the location and likelihood of a landslide event. Finnegan et al., (2021) examined how pre-existing moisture content in the ground influences the onset of motion for slow-moving landslides. They use groundwater hydrology theory and numerical modeling combined with five years of field monitoring to determine how abrupt rises in the water table, resulting from a large precipitation event occurring in

unsaturated soil, can trigger landslide movement. They determined that the dynamics of infiltration through the unsaturated ground at the start of the wet season fundamentally control both the style and timing of landslide response to rainfall. At the start of the wet season there may be no change in pore pressure for weeks to months. However, once the wetting front within the soil reaches the water table, they observed a nearly instantaneous pore water pressure transmission within the landslide body that is accompanied by landslide acceleration. This suggests that the response time of slow-moving landslides is controlled by the depth the water table reaches in the dry season rather than the total landslide thickness.

Strategic Development and Community Engagement

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

ESI played a leading role over the past year in coordinating NASA's Surface Topography and Vegetation (STV) Incubation Study. STV is one of two observables identified as part of the 2018 Decadal Survey's new Incubation program, and is focused on accelerating readiness of lidar, radar, optical, and information technologies to enable cost-effective flight implementation for future missions focused on science related to bare surface land topography, ice topography, vegetation structure, and shallow water bathymetry. An STV Study Team and associated series of ten virtual community workshops assessed the current state of STV science and technology and identified gaps where NASA could focus future investments. The results of the study were published in the STV Incubation Study Team Report (Donnellan et al, 2021).

Both ESI and the Earth Science Technology Office (ESTO) coordinated and led a UAV workshop in March of 2021 to determine the impact that UAVs have or could have in current and future solid-Earth Science missions and projects. This includes the level of science being produced, the needs of the community, new concepts such as coordination with space and ground assets, legal limitations, and technological limitations of different platforms, sensors, and software. This workshop was used to gather community input so that NASA ESI and ESTO can better address and support the progress of UAV science and technology. There were 360 unique participants at this workshop, including members from academia, industry, NASA centers, and other governmental institutions.

Section 1.1.9.5 Water and energy Cycle Focus Area

NASA's Water and Energy Cycle (WEC) focus area supports research aimed at characterizing the dynamics of and the interactions between the two cycles improving the capability to assess and manage water resources and respond to extreme events. Building on the body of work under 1.1.8 "characterizing the behavior of the Earth system," WEC studies seek to improve understanding of the interacting processes that "control the behavior of the Earth system" and hence "improve predictive capability" as described under performance goal 1.1.9. Improving predictive capability in WEC centers on work towards both physics-based and probabilistic forecasting and includes, to an increasing extent, emerging capabilities in machine learning. With this in mind, studies that inform, or develop capabilities to help improve understanding of the future distribution of water and energy, their inter-relationships and impacts on other Earth systems, and the frequency and intensity of extreme events are classified under 1.1.9. An important goal of the Water and Energy cycle is to develop coupled interactive Earth system models that link the atmosphere, oceans, land masses and biosphere into a comprehensive whole. Section 1.1.9 highlights WEC research that focuses on the broader role of water in the global climate, followed by sections on the variations in local weather/precipitation, hydrological hazards/extreme events, and the role of water in food security.

Surface Water

As we saw in Section 1.1.8, WEC is investing in improving our ability to resolve surface water and measure river discharge, especially as we prepare 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. As our models become more sophisticated, they will begin forecasting key surface water parameters such as dynamic runoff routing, snowmelt and river discharge, and lake levels.

Kang *et al.* 2021 ([Environmental Research Letters](#)) studied how to improve forecasts of flooding in the Northern Great Plains of America. This region is flat and has soil that does not readily drain away water. It also receives a lot of snow, and in the spring, a sharp rise in temperature can quickly melt the snow and cause flooding for communities that lie near rivers. In order to better forecast floods like this, the researchers created a model that linked the snow water equivalent of the snow to the streamflow in rivers. They used data from 2002-2011 from the Advanced Microwave Scanning Radiometer-E (AMSR-E) which, through its estimates of snow water equivalent, helped to correct for the underestimates of snowfall that often occur at weather stations in windy areas. These adjustments improved the model estimates of streamflow.

Extreme weather and related hazards

Some of the most visible and disruptive effects of global climate change are extreme weather and resulting disasters such as wildfires and flooding and the resulting cascading

hazards such as landslides and debris flows. These events vary by geographic location, with many regions, such as the Southwest United States and parts of Central and South America, Asia, Europe, Africa and Australia, experiencing more heat, drought and insect outbreaks that contribute to an increase in the number of wildfires. Other regions of the world, including coastal areas of the United States and many island nations, are experiencing flooding and saltwater intrusion into drinking water wells as a result of sea level rise and storm surges from intense tropical storms. Additionally, some areas of the world, such as the Midwestern and Southern United States, have been inundated with rain that has resulted in catastrophic flooding.

Slow-moving landslides are difficult to detect because they often occur in isolated areas that are costly and risky to reach and study. Radar signals that detect the deformation and movement on the Earth surface can therefore be of use. Bekaert *et al.* 2020 ([Remote Sensing of Environment](#)) tested a new analysis that can detect slow-moving landslides, and also measure their size and rate of movement, without need for prior information on where the landslides are located. Their analysis makes use of two years of InSAR (interferometric synthetic aperture radar) which they retrieved from Sentinel-1. Testing this method in the mountains of Nepal, they detected at least six slow-moving landslides and found that rates of movement increased in the year with higher rainfall during the monsoon season. An earthquake that occurred in between the two years of data did not impact the rates of movement, suggesting the earthquake had a negligible effect.

Water Availability

Characterizing where the water currently resides is a major focus for WEC, as described in 1.1.8 above: forecasting and predicting where water will or will not be utilizes this knowledge to better understand water cycle dynamics and to provide relevant and actionable information for decision makers with added societal benefits. Knowing the water availability for food production and ecosystem viability/stress has wide-ranging benefits especially when economic impacts associated too much or too little can be devastating for many countries. As such, it is critical for water resource managers and the agricultural industry to monitor current and future water supplies and to be cognitive of potential extreme flood and drought events. Science efforts that begin within the Research and Analysis Program (RnA) can evolve to support both RnA research and the broader Applied Science Program end user community.

Hall *et al.* 2021 ([Remote Sensing of Environment](#)) looked at the Great Salt Lake of the western US, a lake where snow plays an integral part in regulating the salinity and extent. The researchers used a host of estimates from satellite sensors like MODIS to show that over the last two decades, snow has been melting about 9.5 days earlier. At the same time, air temperatures have increased, the snowfall has decreased, and models show that evapotranspiration has also increased. During the study period, both the elevation of the lake and the area of the lake (captured by Landsat imagery) have fallen. As the lake becomes more saline and shrinks, this both has ecological and recreational implications.

Section 1.1.9.6 Weather and Atmospheric Dynamics Focus Area

For demonstrating progress in **enhancing understanding of the interacting processes that control the behavior of the Earth system, and in utilizing the enhanced knowledge to improve predictive capability**, the WAD invests in understanding precipitation processes, atmospheric dynamics, extreme events including lightning, convective processes, heuristic atmospheric analysis, numerical weather prediction, modeling and data assimilation system improvements.

In order to improve predictive capability, NASA has participated in major data assimilation system software development efforts at the NASA-NOAA-DOD Joint Center for Satellite Data Assimilation (JCSDA). Following the open science and open-source principles, the data assimilation software developed are released to the public and available to all scientists and engineers. After significant development efforts for many years, JCSDA has seen first major software releases in many areas.

The following sections describe the progress made in the past year (2020-2021).

Development and Application of Data Assimilation Systems

Joint Effort for Data Assimilation Integration (JEDI) Development: The Joint Center for Satellite Data assimilation (JCSDA) is a multi-agency research and development center to improve the use of satellite data for analyzing and predicting the weather, the ocean, the climate and, eventually, the Earth system. JEDI is a project at JCSDA to build an integrated data assimilation system for the modern era. It harnesses state of the art object-oriented design practices to build scientific software that is efficient, flexible and easy to use. Central to the idea behind JEDI is that the algorithms used for data assimilation are largely generic and can be built to be useable across centers and thus spread the burden of maintaining that software widely. NASA has embraced the JEDI project as a way to advance the science of data assimilation for its GEOS model and build a system capable of scaling to NASA's ambitious future plans, such as strongly coupled data assimilation. One of the ways in which JEDI will scale well is by harnessing features of the underlying forecast model. Much effort goes into making GEOS and its dynamical core, FV3, scale well and JEDI is being designed to take advantage of that.

Over the course of the last year JCSDA and GMAO made progress on a number of important fronts in regard to developing JEDI for FV3-based models including GEOS. Scientists have developed a static background error model infrastructure and have tested it by producing a prototype background error model. Scientists at GMAO have built a multitude of workflow tools for GEOS and have been able to produce a month-long observation simulation run using these tools as well as run a real time observation monitoring system. These tools will form the environment for GMAO to validate and develop a JEDI-GEOS data assimilation system. In October 2020, JCSDA released the first JEDI system including JEDI-GEOS (<https://www.jcsda.org/news-blog/2020/10/29/jedi-fv3-100-and-crtm-240-releases>) that will be used with GEOS into the public domain. GMAO scientists have contributed across the JEDI system, adding the

capability to perform assimilation for aerosols, ozone and all-sky cloudy microwave radiances. In addition, there are several improvements to the JEDI infrastructure, including adding a generic variable change operator for handling the variable changes needed by GEOS, integrating the cubed-sphere grid of GEOS into the Atlas library and driving forward efficiency gains for the GEOS applications. Other major milestones in this reporting period are CRTM instrument coefficient generation package CRTM_coef v1.0.0 (<https://www.jcsda.org/news-blog/2021/7/2/jcsda-announces-first-crtm-instrument-coefficient-generation-package>) and IODA version 2.0 release (<https://www.jcsda.org/news-blog/2021/6/14/jcsda-announces-jedi-fv3-release-version-110-with-major-ioda-update>). The standardized package exposes the core functionality of the CRTM and allows expert-level users to compute CRTM coefficients for their own MW and IR instruments. The Interface for Observational Data Assimilation (IODA) abstracts access to observations, thus insulating scientists from technical aspects such as file formats.

Sea-ice Ocean and Coupled Assimilation (SOCA) development: As one of the JCSDA projects, SOCA focuses on the application of JEDI to marine data assimilation. One of the goals of SOCA is to make use of surface-sensitive radiances to constrain sea-ice and upper ocean fields (e.g., salinity, temperature, sea-ice fraction, sea-ice temperature, etc.) The focus of this research is to build the first elements toward an ocean/atmosphere coupled data assimilation capability within JEDI, with a focus on supporting and developing the assimilation of radiance observations sensitive to the ocean and atmosphere. Scientists at GMAO are working on the direct radiance assimilation of surface sensitive microwave radiances focusing on Global Precipitation Measurement (GPM) Imager (GMI) for the SST Constraint and Soil Moisture Active Passive (SMAP) for the Sea Surface Salinity (SSS) constraint (Ebrahimi et al., 2020).

Examine the geophysical properties of oceans for weather forecast: Oceans are large and key elements of the Earth's climate system. Among the geophysical properties characterizing them, salinity and temperature are important. Together, they control the density of seawater, and therefore the thermohaline circulation. Thus, these oceanic properties may influence regional weather and climate patterns. While sea surface temperature (SST) is a key component in air-sea exchanges of heat, sea surface salinity (SSS) is required for the determination of surface density which has a significant influence on the global ocean circulation.

With the availability of L-band space-borne observations, it becomes possible to provide global scale sea surface salinity (SSS) distribution. JCSDA and GMAO scientists have analyzed the impact of using the Soil Moisture Active Passive (SMAP) SSS retrievals obtained by JPL and JCSDA and GMAO retrievals using Machine Learning Techniques in the Ocean data assimilation. The impact of the assimilation of the SSS on the salinity analysis has been evaluated by comparisons with in-situ salinity measurements (Ebrahimi et al., 2021).

Improved Prediction of Storm Track and Intensity

Improving the determination of storm intensity: Improvements in the estimation of maximum wind speeds in tropical cyclones (i.e., storm intensity) is demonstrated by two new investigations using the Cyclone Global Navigation Satellite System (CYGNSS) constellation. In the first, presented by Al-Khaldi et al. (2020), the retrieval method is based on the production of a library of simulated CYGNSS observations using a synthetic storm model, as the parameters of the synthetic storm are varied. A matched filter approach between normalized simulated and measured observations is used to retrieve storm parameters. Results using the method are shown for CYGNSS overpasses of Hurricane Irma as a case study. The maximum wind speed estimates have a retrieval root-mean-square difference of 6.89 m/s and a mean difference of 4.52 m/s compared to reported National Hurricane Center Best Track forecasts.

A second method, presented by Cardellach et al. (2020), develops a new retrieval approach for obtaining wind speeds from CYGNSS observations. A variational technique is used based on the direct inversion of a physical forward model. Through comparisons with the background model and other spaceborne sensors (SMAP, SMOS, ASCAT-A/B) the study shows that this new approach has enhanced skill to infer wind speeds, including hurricane force winds. Furthermore, the variational retrieval algorithm is a simplified version of the more general equations that are used in data assimilation, and the calibration scheme could also be integrated in the assimilation process.

Advancing the Prediction of Precipitation

Assimilation of passive microwave information in tropical cyclone simulations: Moradi et al. (2020) developed a retrieval algorithm known as the Bayesian Monte Carlo Integration technique and then assimilated the retrieved fields (temperature, humidity, cloud liquid and ice water content) into a simulation of a tropical cyclone using the NASA Global Earth Observing System (GEOS) model and a four-dimensional ensemble variational assimilation approach. The assimilation of the retrievals led to improvements in the forecasted intensity in terms of maximum wind speeds and the strength of the warm core. However, little impact was seen on storm track and minimum central pressure. Another study focused on a tropical cyclone was by Shen et al. (2021), this time doing direct assimilation of the GMI clear-sky radiance measurements (i.e., excludes precipitation impacted radiances) in the Weather Research and Forecasting (WRF) model and using a 3-dimensional ensemble variations assimilation system. The results demonstrate improved depiction of the tropical cyclone warm core and improved short-term forecasts of storm track and intensity.

Implementation of all-sky passive microwave assimilation to improve forecasts: Kim et al. (2020) made a major advance by implementing all-sky GMI assimilation in the NASA GEOS model, allowing for incorporation of precipitation information into the analysis. To do so, they needed to incorporate new microphysical variables related to clouds and precipitation and improve forward models needed to simulation their influence on brightness temperatures. From single-observation experiments, they demonstrate the potential of all-sky brightness temperature assimilation to impact thermodynamic and

dynamic fields, and report that assimilation in the operational GEOS system leads to improved short-term forecasts.

Operation implementation of GPM radar data assimilation: Assimilation of spaceborne radar data is much less common. Ikuta et al. (2020) developed a one-dimensional maximum-likelihood estimation assimilation approach that uses GPM DPR data to estimate relative humidity profiles that are then assimilated into the Japanese Meteorological Agency (JMA) forecast model. The approach has been used operationally by JMA since March 2016.

Assimilation of IMERG multi-satellite precipitation products: Zhang et al. (2020) tested assimilation of GPM IMERG rainfall estimates using a 4-dimensional variational assimilation system and the WRF model, experimenting with 1- and 6-hour assimilation windows and logarithmically transformed and non-transformed data. In general, 1-hour assimilation windows performed better than 6-hours, and logarithmically transforming the rainfall values did not have much impact relative to non-transformed data. However, forecasts of heavy precipitation events were improved if the observation error is transformed into logarithmic space.

Evaluation of multi-satellite rainfall products for landslide applications: Ozturk et al. (2021) evaluated two rainfall products, satellite derived estimates using the Integrated Multi-satellitE Retrieval for GPM (IMERG) and the European Centre for Medium-Range Weather Forecasts reanalysis data from ERA-5, within a linear regression model to determine whether these rainfall products can produce accurate spatial variability of rainfall and improve hindcasting landslides at two sites in Japan. Additionally, the authors used precipitation data collected from ground-based radars as benchmarks. The model used a limited number of geomorphometric and geologic predictors, leaving room for the different rainfall products and test whether these variables increase the performance of the model. Their findings show that ground-based radar derived rainfall estimates significantly increased model performance breaching 90%, however IMERG and ERA-5 rainfall products increased model performance by only ~7%. The authors suggest this shortcoming to the lack of spatial consistency and ability to locate storm centers. The authors further suggest that global rainfall products are potentially beneficial for landslide hindcasting, but improvements are needed in capturing spatial rainfall patterns rather than rainfall amounts.

Application of multi-satellite rainfall products for landslides in India: Rainfall-induced landslides attribute to many fatalities in India and are a major public concern. Using rainfall estimates from the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA-3B42 V7) product and the Global Precipitation Mission's (GPM) Integrated Multi-satellitE Retrieval for GPM (IMERG) version 5 final and real-time (RT) products, Thakur et al. (2020) analyze three rainfall-induced landslide events over Western Ghats (WG) of India to examine the capability of satellite estimated rainfall data in monitoring landslide occurrences over this region. Daily gridded rainfall data from the India Meteorological Department (IMD) and Weather Research and Forecasting (WRF) numerical model simulations are also used to compare the satellite derived

rainfall products and understand the efficiency of both multi-satellite products. The authors conducted a comparative analysis of the multi-satellite products with IMD and WRF and show that IMERG is able to capture increased rain rates and rainfall distribution more reliably around a landslide event. They propose that IMERG V5 can be used as an indicator to reliably depict the higher rainfall scenario over the WG region, which is advantageous for real time monitoring of landslides.

Downscaling multi-satellite precipitation products to fine scales: Yan et al. (2021) apply a downscaling–merging scheme based on random forest and cokriging to develop a high-precision and high-resolution precipitation data set. The scheme is applied to downscale the Global Precipitation Measurement Mission’s (GPM) multi-satellite product, the Integrated Multi-satellitE Retrieval for GPM (IMERG), over the upstream part of the Hanjiang Basin at a scale of 0.01 degrees. The authors demonstrate that the downscaling model based on random forest can correctly spatially downscale IMERG while retaining the accuracy of the original GPM data. The authors also show that the IMERG product can be downscaled on the seasonal scale and the merging method based on cokriging greatly improves the accuracy of the downscaled IMERG product. The study concludes that this process provides an efficient scheme for generating high-resolution and high-quality daily precipitation data over a large area.

Application of multi-satellite precipitation products to rainfall runoff simulations: Feng et al. (2021) present a case study to evaluate the effectiveness of multiple precipitation data products to simulate runoff at a small watershed scale. Specifically, the authors used six precipitation products, PERSIANN, PERSIANN-CDR, TRMM-3B42V7, GPM IMERG, Stage IV, and ERA5, as input to drive the coupled routing and excess storage (CREST) distributed hydrological model to evaluate the runoff simulation within small watersheds distributed in nine different geographic regions in the United States. Result shows the precipitation products match the NOAA-CPC-US from high to low in the order of Stage IV, PERSIANN-CDR, GPM-IMERG, PERSIANN, ERA5, and finally TRMM3B42 V7. The authors note that relatively low accuracy is exhibited in the northern high latitude area and the western mountains, while there is better accuracy in the central, southern, and eastern parts of the United States. In the runoff simulation effectiveness evaluation, the daily runoff of watersheds is simulated during the same period. These results show that: NOAA-CPC-US and Stage IV product have good simulation effect in small watersheds. In the northern and western United States, the authors suggest that PERSIANN, PERSIANN-CDR, GPM-IMERG, and ERA5 products for runoff simulation should be used with caution. They conclude that TRMM-3B42V7 is not suitable for runoff simulation in small watersheds.

Identifying optimal forcing intervals for rainfall runoff simulations: Limited sampling of precipitation estimates from passive microwave constellations can severely impact applications such as model-based hydrological studies involving extreme flood and drought monitoring. To evaluate the impact of orbital sampling on streamflow simulations, Pradhan et al. (2021) use orbital data from the Global Precipitation Measurement (GPM) Dual Precipitation Radar (DPR) 2A-Ku product within the Variable Infiltration Capacity (VIC) model to derive ensembles of runoff simulations. The

objective of the study is to find the optimum forcing integration time of orbital data product with narrow swath width that would minimize sampling uncertainty in the simulation of streamflow. To simulate GPM orbital data products, ensembles of synthetic precipitation fields were generated at different sampling intervals with the Satellite Rainfall Error Model (SREM-2D) over the Hirakud catchment in the Indian subcontinent over a period of two years (2015–2016). The NOAA-NCEP Climate Prediction Center (CPC) morphing technique (CMORPH) satellite-based gridded rainfall product is considered as the reference rainfall in the study. The results from the study indicate that streamflow simulations from VIC model using precipitation forcing at 6-hourly integration outperforms the simulations as compared to 3-hourly and 12-hourly forcing integration times, where the relative Root-Mean-Square-Error (RMSE) is highest for the 12-hourly forcing for both years. The authors conclude that a generic framework is necessary to study the manifestation of satellite constellation sampling uncertainty in hydrologic simulations, which are crucial for future missions such as the CubeSat-based Temporal Experiment for Storms and Tropical Systems, and the Time-Resolved Observations of precipitation structure and storm intensity with a constellation of smallsats.

Evaluating hydrological modeling in urban areas in Brazil: Getriana et al. (2020) examine how satellite-based rainfall estimates from the Global Precipitation Measurement (GPM) mission can inform hydrometeorological modeling capabilities for natural disasters at a city scale and evaluate the impact on simulating processes that influence floods and landslides within urban areas. The authors use two rainfall products derived from GPM's multi-satellite product, Integrated Multi-satellite Retrievals for GPM (IMERG) Early and IMERG Final products and integrate them into the Noah Multi-Parameterization (Noah-MP) land surface model to simulate the spatial and temporal dynamics of two key hydrometeorological disaster triggers across the city of Rio de Janeiro over the wet seasons during 2001–2019. The authors selected 33 ground-based observations to interpolate, and the results were used in an in-situ precipitation-based simulation that was considered as a benchmark for evaluating IMERG-driven simulations. The results show that IMERG is moderate in detecting extreme events, with IMERG Final performing slightly better for most metrics. The authors further described that IMERG detects mostly hourly extreme events, but underestimates rainfall rates, resulting in underestimated total runoff and rootzone soil moisture that are considered as flood and landslide triggers, respectively. The authors demonstrate that GPM satellite products have significantly improved skill in detecting extreme events, indicating that IMERG precipitation could be potentially used as a predictor for natural disasters in urban areas.

Understanding precipitation impacts on transportation: The GPM Mission Applications Team, in collaboration with the Aerosols, Clouds, Convection and Precipitation (ACCP) Study Applications Impact Team (AIT), organized the virtual 2020 NASA GPM-ACCP Transportation and Logistics Workshop in November 2020. The workshop consisted of a mixture of scientific sessions, panels, and breakouts that brought together ~70 representatives from NASA, federal and state operational agencies, private companies, and boundary organizations to discuss how NASA precipitation and cloud products could be better leveraged to inform decision making for current and future operations of

aviation, maritime, and road and highway transportation systems. Within the report, Portier and Kirschbaum (2020) present an overview and lessons learned from the 2020 NASA GPM-ACCP Transportation and Logistics Workshop.

A tool for visualizing and analyzing tropical cyclone precipitation: Hristova-Veleva et al. (2020) highlighted the development of the Tropical Cyclone Information System (TCIS)—a data analytic framework that integrates model forecasts with multiparameter satellite and airborne observations, providing interactive visualization and online analysis tools. TCIS tool provides quick investigation of the structure of the tropical storms and their environments. The paper then provides an overview of the TCIS's components and features. It also summarizes recent pilot studies, providing examples of how the TCIS has inspired new research, helping to increase the understanding of tropical cyclones. The authors conclude that TCIS allows atmospheric scientists to focus on new ideas and concepts hosted in one location rather than researching data scattered over several agencies.

Using rainfall and surface soil moisture to improve river runoff estimates: Brocca et al. (2020) present a study using three developed rainfall products integrating data from GPM and satellite soil moisture products namely, GPM+SM2RAIN, PRISM-SMOS, and PRISM-SMAP, to test the prediction of daily river discharge across 10 basins located in Europe (4), West Africa (3) and South Africa (3). The authors also compare these rainfall products to GPM's IMERG Early product, rain gauges, and the European Centre for Medium-Range Weather Forecasts reanalysis product, ERA5. For the study, the authors use then three different conceptual and lumped rainfall-runoff models to obtain results over the 3-year data period of 2015–2017. Results indicate, particularly in West Africa, the integrated products outperform both ground- and reanalysis-based rainfall estimates. For all basins, the GPM+SM2RAIN product outperforms among the short latency products, and significantly better than GPM Early. The integrated products are found to reproduce particularly well the high flows. The authors conclude that results highlight the strong need to disseminate such integrated satellite rainfall products for hydrological and agricultural applications in poorly gauged areas such as Africa and South America.

Evaluating IMERG rainfall products for fire applications: Alaska fire managers use the Canadian Forest Fire Danger Rating System (CFFDRS) operationally to disseminate statewide fire weather outlooks and forecasts for wildfires events. The CFFDRS relies heavily on a small number of in-situ stations across Alaska for meteorological observations, with precipitation being a critical observation. To improve the spatial coverage of precipitation across Alaska, Gowan et al. (2020) evaluate near-real-time daily precipitation estimates from the IMERG algorithm during six fire seasons from 2014-2019. IMERG was verified using 322 in-situ stations across four Alaska regions. Empirical cumulative distributions of daily precipitation were taken from station observations and compared to corresponding distributions of interpolated values from IMERG grid points. The authors show that IMERG exhibited wet biases. A bias correction approach using regional quantile mapping was developed to mitigate for the IMERG wet bias. The results indicated that the bias-adjusted IMERG were found to improve gridded IMERG estimates. The authors concluded that this approach may help

improve situational awareness of wildfire potential across Alaska and may be appropriate to use in other high-latitude regions where in-situ observations are sufficient to help correct IMERG estimates.

Studying environmental predictors of malarial risk: Time series models have been applied to forecast epidemics and support public health initiatives. Using a new modeling approach, Davis et al. (2019) combines standard time series techniques with a genetic algorithm to identify an optimal clustering of districts for environmental modeling of malaria risk. The authors used seven years of weekly Plasmodium falciparum data from 47 districts throughout the Amhara Region of Ethiopia and remotely sensed land surface temperature using Terra MODIS, precipitation from GPM IMERG, and spectral indices calculated from MODIS nadir bidirectional reflectance distribution function adjusted reflectance (NBAR) as predictors. The best model identified six clusters, and the districts in each cluster had distinctive responses to the environmental predictors. The authors conclude that spatial stratification can improve the fit of environmentally driven disease models, and genetic algorithms provide a practical and effective approach for identifying these clusters.

Operational Applications of Global Precipitation Measurement (GPM) Observations: The NASA Global Precipitation Measurement Mission core satellite was launched in 2014, and the data observations provided by this mission are freely available to scientists around the globe in near real time. As part of the Early Adopter program, NASA's Short-term Prediction Research and Transition (SPoRT) center has worked to provide these data to National Weather Service forecasters and hydrologists to determine its value within the operational environment (LeRoy et al. 2020). Over the course of three formal assessments with targeted users, forecasters have provided feedback to SPoRT on what types of data and value-added products are relevant to the offices' primarily forecast challenges, how these GPM precipitation datasets can best be displayed, and what the products' value is for specific weather-related phenomena. Forecasters in operational weather forecasting and hydrology valued using the precipitation estimate data, particularly in heavy rain events in which the impacts could be dangerous. These types of events include areal flooding from atmospheric river events, flash flooding from convective events, and assessing precipitation for mudslide risks. The gridded precipitation dataset from GPM, called IMERG, provided the most value to hydrologists. IMERG also provided some value to forecasters in retrospective cases, due to its longer latency. Snowfall-related products derived from GPM helped forecasters assess the intensity and location of falling snow, supplementing other datasets like ground-based radar. The passive microwave imagery, including RGB composites of different polarizations of single channels, helped tropical forecasters infer structure and intensity in tropical systems. The details and context of these results are provided herein to guide possible operational use of GPM's datasets for forecasting and nowcasting.

Investigating Soil Moisture Responses Associated with Significant Tropical Cyclone Events:

Tropical cyclones (TCs) present several hazards to impacted coastal and inland populations, including damaging winds, storm surge along the coast, tornadoes, and

extensive inland freshwater flooding. The severity of inland flooding depends on many factors such as (i) storm motion (that affects storm total rainfall) determined by atmospheric steering currents, (ii) extratropical transition and downstream impacts, (iii) local geography, topography, and/or urbanization, and (iv) antecedent soil moisture conditions and how it can sustain or modulate inland tropical cyclones. SPoRT scientists used historical and real-time output from the observations-driven SPoRT-LIS running the Noah LSM at ~3-km grid spacing across the CONUS, an analysis of the modeled soil moisture responded to each multi-day rainfall event, typically transitioning from below median/anomalously dry soils in the pre-storm environment to record or near-record high soil wetness levels in the post-storm state. Time series analyses of county-averaged percentiles were presented to document soil moisture conditions leading up to each event, the abrupt pre- to post-storm transitions, and the residence time of the anomalously moist soils following each TC (Case et al. 2021).

Improving the Atmospheric Models and Prediction

Improving convective cloud and convective parameterizations: NASA funded scientists recently used AIRS temperature and water vapor retrievals in two ways: 1) to inform process-level parameterization development in global climate models (GCMs), and 2) to evaluate emergent properties of the CMIP6 GCMs. The process-level approach focuses on organized convection parameterization in GCMs. Schiro et al. (2020) noted the importance of anomalous moisture leading convective organization only hours before heavy rainfall, suggesting that the mesoscale state plays a more important role than the slowly changing large-scale state in heavy convective rainfall. The AIRS moisture and buoyancy fields have also been used to constrain a new analytical source-sink model for convective anvil area time tendencies (Elsaesser et al., 2021). This new model will serve as a foundation for GISS GCM anvil area parameterization development. The evaluation of CMIP6 GCM climatologies has resulted in two papers: one on the evaluation of the GISS-GCM (Kelley et al., 2020) that uses AIRS column water vapor constraints, and the other on the evaluation of the suite of CMIP6 GCM water vapor profile climatologies (Jiang et al., 2021). The joint process-level and mean state evaluation approach ensures that improved GCM mean states occur for the right process-level reasons, an important endeavor for ensuring greater reliability in GCM projections.

Use of AIRS and CrIS cloudy radiance in tropical cyclone forecasting: Previous work published by this team demonstrated a positive impact on tropical cyclone forecasting consequent to the assimilation of AIRS cloud-cleared radiances (CCRs) in a global data assimilation and forecast system. Two new articles demonstrated additional improved capabilities consequent to the assimilation of CCRs in regions away from the tropics (McGrath-Spangler et al. 2021; Ganeshan et al., 2021). The first article shows an improvement of the thermal structure representation in the Arctic lower troposphere, leading to more accurate forecasts of individual high-latitude weather systems. The second article shows the improvement on the representation of intense small-scale convectively-driven cyclones such as polar lows. Ongoing work is striving to further enhance the impact of CCRs from AIRS and CrIS on the predictive capabilities, by improving the portability and speed of the cloud-clearing algorithm, and by using an

adaptive strategy that allows to assimilate more data in proximity of tropical cyclones. In addition to the two papers submitted, the team gave 7 virtual presentations at national and international events.

Improving assimilation of infrared radiances impacted by dust: Through Office of Naval Research, a NASA funded project has built a new retrieval for thin, translucent cirrus cloud occurrence in daytime geostationary NOAA ABI 1.378 μm band radiances. A near real-time product has further been developed over water that supplements the cloud mask with cloud top height, temperature and effective radius information. A paper describing the mask has just been published (McHardy et al. 2021). These data can now supplement the use of climatological cirrus cloud information in ongoing tests on the operational system in FY22. Other efforts continue to examine the impact of dust (Marquis, 2021) and cirrus contamination (in preparation) on hyperspectral infrared radiances, where scientists estimate the aerosol and cloud optical depth upon which the contamination is undetected by current radiance screening methods. Lastly, work was done to modify the Navy global NAVGEM system to use the NASA near real time AIRS data feed and changes passed along to the operational partner Fleet Numerical Meteorology and Oceanography Center. NRL Marine Meteorology Division (MMD) has also begun a 19-year reanalysis effort beginning in 2003. NRL's AIRS archive began in Jun2008 so NRL scientists have incorporated processing to backfill the AIRS archive, this obtains data from the NASA archive does spectral and spatial sampling and generated BUFR files mimicking the operational data feed allowing inclusion of this critical data in the re-analysis effort.

AIRS Obs4MIPs V2.1 dataset: JPL scientists estimate the sampling biases of the Atmospheric Infrared Sounder (AIRS) Observations for Model Intercomparison Projects (Obs4MIPs) Version 2.0 (V2.0) monthly mean tropospheric air temperature, specific humidity and relative humidity profile data based on the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) (ERA5) reanalysis and cross-check them using the Modern-Era Retrospective Analysis for Research and Application, Version 2 (MERRA-2) reanalysis. Scientists then remove the estimated sampling biases from the AIRS Obs4MIPs V2.0 data and produce the sampling-bias-corrected AIRS Obs4MIPs V2.1 data that has been published at the Earth System Grid Federation (ESGF) data centers and should be used in the future for climate model evaluation (Tian and Hearty, 2020). The evaluation of Coupled Model Intercomparison Project Phase 6 (CMIP6) models using the AIRS Obs4MIPs V2.1 data is ongoing.

Improving the Prediction of Tropical Wetland Methane Emission: Wetlands are the single largest source of methane to the atmosphere and their emission is expected to respond to a changing climate. Inaccuracy and uncertainty in inundation extent drives differences in modeled wetland emissions and impacts representation of wetland emissions on inter-annual and seasonal time frames. Existing wetland maps are based on optical or NIR satellite data obscured by clouds and vegetation, often leading to underestimates in wetlands extent, especially in the Tropics. Gerlein-Safdi et al. (2021) present new inundation maps based on the CYGNSS satellite constellation. Notably, the

maps are not impacted by clouds or vegetation, providing reliable observations through canopy and cloudy periods. The temporal and spatial dynamics of the Pantanal and Sudd wetlands, two of the largest wetlands in the world, are mapped using CYGNSS data and a computer vision algorithm. These wetland inundation maps are used as to force WetCHARTs, a global wetland methane emissions model ensemble, to predict resulting methane fluxes. The CYGNSS-modeled methane emissions are compared to WetCHARTs standard runs that use monthly rainfall data from ERA5, as well as the commonly used SWAMPS wetland maps. CYGNSS-based inundation maps are found to modify the methane emission in several important ways. The seasonality of inundation and methane emissions is shifted by approximately two months due to the lag in wetland recharge following peak rainfall. Both inundation and methane emissions also respond non-linearly to wet-season precipitation totals, leading to large inter-annual variability in emission. Finally, the annual magnitude of emissions is found to be significantly greater than that estimated by existing methods.

Lightning Prediction and Interactions

Using Lightning to Identify Tropical Cyclone Intensity Change: SPoRT analyzed the two most distinct inner-core lightning outbreaks in Hurricane Dorian (2019) using the Geostationary Lightning Mapper (GLM). The first outbreak occurred during Dorian's intensification, including a rapid intensification (RI), and the second occurred during weakening. During RI, inner-core lightning flash density increased as flashes concentrated inside of the radius of maximum wind (RMW). As weakening commenced, numerous flashes still occurred within the RMW, with a flash rate more than three times that during RI—a signal typically associated with strengthening. These flashes, however, were much smaller and less energetic than those during intensification. Evidence is presented that barotropic mixing and secondary eyewall formation increased the number of small, low-energy lightning flashes in the inner core while simultaneously weakening the storm. The results suggest that flash area and energy from GLM could help distinguish between lightning outbreaks that correspond to intensification and those that correspond to weakening (Duran et al. 2021b)

Observations of lightning in relation to transitions in volcanic activity during the 3 June 2018 Fuego Eruption: Satellite and ground-based remote sensing are combined to characterize lightning occurrence during the 3 June 2018 Volcán de Fuego eruption in Guatemala. The combination of the space-based Geostationary Lightning Mapper (GLM) and ground-based Earth Networks Total Lightning Network observed two distinct periods of lightning during this eruption totaling 75 unique lightning flash occurrences over five hours (57 in cloud, 18 cloud-to-ground). The first period of lightning coincided with the rapid growth of the ash cloud, while the second maxima occurred near the time of a deadly pyroclastic density current (PDC) and thunderstorm. Ninety-one percent of the lightning during the event was observed by only one of the lightning sensors, thus showing the importance of combining lightning datasets across multiple frequencies to characterize electrical activity in volcanic eruptions. GLM flashes during the event had a median total optical energy and flash length of 16 fJ, and 1km, respectively. These median GLM flash energies and lengths observed in the volcanic plume are on the lower

end of the flash spectrum because flashes observed in surrounding thunderstorms on 3 June had larger median total optical energy values (130 fJ) and longer median flash lengths (20 km). All 18 cloud-to-ground flashes were negative polarity, supportive of net negative charge within the plume. Mechanisms for the generation of the secondary lightning maxima are discussed based on the presence and potential interaction between ash plume, thunderstorm, and PDC transport during this secondary period of observed lightning.

Investigation of cloud-to-ground flashes in the Non-precipitating stratiform region of a Mesoscale Convective System on 20 August 2019 and Implications of Decision Support Services: Infrequent lightning flashes occurring outside of surface precipitation pose challenges to Impact-based Decision Support Services (IDSS) for outdoor activities. This paper examines the remote sensing observations from an event on 20 August 2019 where multiple cloud-to-ground flashes occurred over 10 km outside surface precipitation (lowest radar tilt reflectivity <10 dBZ and no evidence of surface precipitation) in a trailing stratiform region of a mesoscale convective system. The goal is to demonstrate the fusion of radar with multiple lightning observations and a lightning risk model to demonstrate how reflectivity and differential reflectivity combined provided the best indicator for the potential of lightning where all of the other lightning safety methods failed. Thirteen lightning flashes were observed by the Geostationary Lightning Mapper (GLM) within the trailing stratiform region between 2100 and 2300 UTC. The average size of the thirteen lightning flashes was 3184 km², with an average total optical energy of 7734 fJ. Seventy-five NLDN flash locations were coincident with the thirteen GLM flashes, resulting in an average of 5.8 NLDN flashes (in-cloud (IC) and cloud-to-ground (CG)) per GLM flash. Five of the GLM flashes contained at least one positive cloud-to-ground flash (+CG) flash identified by the NLDN, with peak amplitudes ranging between 66 and 136 kA. All eight CG flashes identified by the NLDN were located more than 10 km outside surface precipitation. The only indication of the potential of these infrequently large flashes was the presence of depolarization streaks in differential reflectivity (Z_{DR}) and enhanced reflectivity near the melting layer.

A Spatiotemporal lightning risk assessment using lightning mapping data: A lightning risk assessment for application to human safety was created and applied in 10 west Texas locations from 2 May 2016 to 30 September 2016. The method combined spatial lightning mapping data, probabilistic risk calculation adapted from the International Electrotechnical Commission Standard 62305-2, and weighted average interpolation to produce risk magnitudes that were compared with tolerability thresholds to issue lightning warnings. These warnings were compared with warnings created for the same dataset using a more standard lightning safety approach that was based on National Lightning Detection Network (NLDN) total lightning within 5 n mi (1 n mi = 1.852 km) of each location. Four variations of the calculation as well as different units of risk were tested to find the optimal configuration to calculate risk to an isolated human outdoors. The best-performing risk configuration using risk (10 min)⁻¹ or larger produced the most comparable results to the standard method, such as number of failures, average warning duration, and total time under warnings. This risk configuration produced fewer failures than the standard method but longer total time under warnings and higher false alarm

ratios. Median lead times associated with the risk configuration were longer than the standard method for all units considered, whereas median down times were shorter for risk $(10 \text{ min})^{-1}$ and risk $(15 \text{ min})^{-1}$. Overall, the risk method provides a baseline framework to quantify the changing lightning hazard on the storm scale and could be a useful tool to aid in lightning decision support scenarios.

Advanced Baseline Imager Cloud-Top Trajectories and Properties of Electrified Snowfall

Flash Initiation: Using gridded and interpolated Derived Motion Winds from the Advanced Baseline Imager (ABI), a Lagrangian cloud-feature tracking technique was developed to create and document trajectories associated with electrified snowfall and changes in cloud characteristics leading up to the initiation of lightning, respectively. Harkema et al. (2021) implemented the thundersnow detection algorithm and defined thundersnow initiation (TSI) as the first group in a flash detected by the Geostationary Lightning Mapper when snow was occurring. Ten ABI channels and four multispectral (e.g., red-green-blue–RGB) composites were analyzed to investigate characteristics that lead up to TSI for 16,644 thundersnow (TSSN) flashes. From the $10.3 \mu\text{m}$ channel, TSI trajectories were associated with a median decrease of 12.2 K in brightness temperature (TB) one hour prior to TSI. Decreases in the reflectance component of the $3.9 \mu\text{m}$ channel indicated that TSI trajectories were associated with ice crystal collisions and/or particle settling at cloud-top. The Nighttime Microphysics, Day Cloud Phase Distinction, Differential Water Vapor, and Airmass RGBs were examined to evaluate the microphysical and environmental changes prior to TSI. For daytime TSI trajectories, the predominant colors associated with the Day Cloud Phase Distinction RGB transitioned from cyan to yellow/green, physically representing cloud growth and glaciation at cloud-top. Gold/orange hues in the Differential Water Vapor RGB indicated that some trajectories were associated with dry upper-level air masses prior to TSI. The analysis of ABI characteristics prior to TSI, and subsequently relating those characteristics to physical processes, inherently increases the fundamental understanding and ability to forecast TSI; thus, providing additional lead-time into changes in surface conditions (i.e., snowfall rates, visibilities).

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