EARTH SCIENCE DIVISION

TABLE OF CONTENTS

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, we report here highlights of ACFA sponsored research published since July 2022 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 gaps inhererent in the high temporal and spatial variability of the ground-based air quality networks with a combination of new space-borne measurements well as expansion of ground-based networks

(c) improve estimates of emissions of greenhouse gases such as CO_2, methane (CH_4) and nitrous oxide (N_2O) in order to better understand their variability in space and in time and to support international efforts such as the Global Stocktake,

(d) use NASA's portfolio of space-based instruments such as the Ozone Monitoring Instrument (OMI) and the Microwave Limb Sounder (MLS) on the Aura satellite together with key ground-based networks like the Advanced Global Atmospheric Gases Experiment (AGAGE) and the Southern Hemisphere Additional Ozonesondes (SHADOZ) to characterize the evolution of the multi-decadal ozone recovery process, ongoing changes in radiative forcing, and to 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 at higher accuracy and resolution than possible from space.

B. Aerosols, clouds and radiative forcing

The ACFA Radiation Sciences Program (RSP) and associated space-borne missions and sub-orbital projects support a broad range research on aerosols, clouds and the Earth's radiative flux. Here we summarize seven papers on aerosol remote sensing and retrievals and dust observations.

Aerosol remote sensing and retrievals

Kahn and Samset (2022) describe the principles of aerosol satellite measurements and retrieval algorithms, and surveys past and current instruments and their capabilities. They outline the issues associated with retrieving aerosol properties, such as surface characterization and aerosol proximity to clouds, and the challenges with interpretation of the results. They review how satellite remote sensing instruments have been used to evaluate aerosol representations in global climate models, which have revealed generic biases in their regional aerosol amounts and seasonal patterns of transport and removal. Some of the challenges involved in model-observation comparison are outlined, in particular how substantial errors can be introduced unless attention is paid to spatial and temporal collocation, cloud screening, subgrid-scale variability, and measurement uncertainties that vary with retrieval conditions.

The NASA Cloud, Aerosol, and Monsoon Processes Philippines Experiment (CAMP2Ex) employed the NASA P-3, Stratton Park Engineering Company (SPEC) Learjet 35, and a host of satellites and surface sensors to characterize the coupling of aerosol processes, cloud physics, and atmospheric radiation within the Maritime Continent's complex southwest monsoonal environment. Conducted in the late summer of 2019 from Luzon, Philippines, in conjunction with the Office of Naval Research Propagation of Intraseasonal Tropical Oscillations (PISTON) experiment with its R/V *Sally Ride* stationed in the northwestern tropical Pacific, CAMP2Ex documented diverse biomass burning, industrial and natural aerosol populations, and their interactions with small to congestus convection. As discussed by **Reid et al. (2023)** the 2019 season exhibited El Niño conditions and associated drought, high biomass burning emissions, and an early monsoon transition allowing for observation of pristine to massively polluted environments as they advected through intricate diurnal mesoscale and radiative environments into the monsoonal trough. CAMP2Ex's preliminary results indicate that 1) increasing aerosol loadings tend to invigorate congestus convection in height and increase liquid water paths; 2) lidar, polarimetry, and geostationary Advanced Himawari Imager remote sensing sensors have skill in quantifying diverse aerosol and cloud properties and their interaction; and 3) high-resolution remote sensing technologies are able to greatly improve our ability to evaluate the radiation budget in complex cloud systems.

Current Earth system models reveal significant differences in estimates of regional aerosol radiative effects over the Southeast Atlantic Ocean associated with large smoke layers. **Chang et al. (2023a)** examine differences in the models' representations of aerosol optical depth and vertical distribution using measurements from the NASA Langley Research Center High Spectral Resolution Lidar-2. The models generally underestimate aerosol optical depths (AODs) for measured AODs above 0.8, indicating limitations at reproducing high AODs. These differences in the absolute AOD, free troposphere AOD, and the vertical apportioning of AOD in different models revealed by the HSRL-2 measurements highlight the need to continue improving the accuracy of modeled AOD distributions.

Fires in southern Africa emit approximately one-third of the world's carbon and appropriate representations of the distinct aerosol composition are needed to realistically depict regional aerosol radiative effects. Aerosol over the remote southeastern Atlantic is some of the most sunlight-absorbing aerosol on the planet: the free-tropospheric single-scattering albedo (SSA) at the 530 nm wavelength ranges from 0.83 to 0.89 based on in-situ data from the ORACLES (ObseRvations of Aerosols above CLouds and their intEractionS) aircraft flights from late August–September. **Dobracki et al. (2023)** account for this high SSA using the organic aerosol to refractory black carbon mass ratio (OA:rBC). They find that as biomass-burning aerosol is transported westward off of the African continent, heterogeneous oxidation can fragment the organic aerosol as the aerosol ages, allowing the aerosol to enter the gas phase and reducing the organic aerosol mass.

To reduce high radiative forcing uncertainties associated with aerosol-cloud interactions (ACI), it is important to better constrain global Cloud Condensation Nuclei (CCN) distributions. **Lenhardt et al. (2023)** develop an approach to estimate vertically resolved CCN concentrations using relationships between *in situ* CCN concentration and aerosol backscatter and extinction coefficients measured by the NASA Langley Research Center High Spectral Resolution Lidar-2 (HSRL-2). These lidar-derived CCN concentrations can be used to evaluate model performance, which is illustrated using an example CCN concentration curtain from the Weather Research and Forecasting (WRF) model coupled with physics packages from the Community Atmosphere Model version 5 (WRF-CAM5). These results demonstrate the utility of deriving vertically resolved CCN concentrations from lidar observations to expand the spatiotemporal coverage of limited or unavailable *in situ* observations.

Dust

Climate change can cause a decrease in the duration of snow cover, retreat of glaciers, and an increase in drought, heatwave intensity, and frequency, leading to the increasing frequency of topsoil conditions favorable for dust emission. **Meinander et al. (2023)** identify, describe, and quantify the intensity of 64 high-latitude dust (HLD) sources using the Global Sand and Dust Storms Source Base Map (G-SDS-SBM). Activity from most of these HLD sources shows seasonal character and greatly depends on weather conditions. They show evidence a northern HLD belt and using the global atmospheric transport model SILAM, estimate that 1.0 % of the global dust emission originated from the high-latitude regions. About 57 % of the dust deposition in snow- and ice-covered Arctic regions was from HLD sources while in the HLD region of the Southern Hemisphere, soil surface conditions are favorable for dust emission during the whole year.

Spatial distributions of aerosol particles have a potentially large influence on climate-relevant cloud properties but can be difficult to observe over the Arctic given pervasive cloudiness, long polar nights, data paucity over remote regions, and periodic diamond dust events that satellites can misclassify as aerosol. **Zamora et al. (2023)** compare Arctic 2008–2015 mineral dust and combustion aerosol distributions from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite, the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis products, and the FLEXible PARTicle (FLEXPART) dispersion model. Based on coincident, seasonal Atmospheric Infrared Sounder (AIRS) Arctic satellite meteorological data, diamond dust may occur up to 60 % of the time in winter, but hardly ever in summer. In its absence, MERRA-2 and FLEXPART each predict the vertical and horizontal distribution of large-scale patterns in combustion aerosols with relatively high confidence. CALIPSO is likely misclassifying diamond dust as mineral dust FLEXPART may be overpredicting local dust emissions. All three products predicted that wintertime dust and combustion aerosols occur most frequently over the same Siberian regions where diamond dust is most common in the winter. This assessment paves the way for applying the model-based aerosol simulations to a range of regional-scale Arctic aerosol–cloud interaction studies with greater confidence.

C. *Tropospheric composition, air quality, biomass burning & wildfires and health effects of air pollution*

Research supported by the ACFA Tropospheric Composition Program (TCP) 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. Summarized in this subsection are sixteen papers in six topic areas: air quality measurements and characterization, COVID-19 impacts on tropospheric composition and air quality, carbon monoxide measurements and long-term changes, the FIREX-AQ program and wildfire impacts on air quality and measurements of tropospheric composition, including atmospheric ammonia.

Tzortziou et al. (2023) integrated measurements from different platforms – boats, ground-based networks, aircraft, and satellites – to characterize total column NO2 (TCNO2) dynamics across the land-water continuum in the New York metropolitan area during the 2018 Long Island Sound Tropospheric Ozone Study (LISTOS). Measurements were conducted, with a main goal to extend surface measurements beyond the coastline – where ground-based air-quality monitoring networks abruptly stop – and over the aquatic environment where peaks in air pollution often occur. Satellite TCNO2 from TROPOMI correlated strongly with Pandora surface measurements (r = 0.87, N = 100) both over land and water. Yet, TROPOMI overall underestimated TCNO2 (MPD = -12%) and missed peaks in NO2 pollution caused by rush hour emissions or pollution accumulation during sea breezes. Aircraft retrievals were in excellent agreement with Pandora (r = 0.95, MPD = -0.3%, N = 108). Stronger agreement was found between TROPOMI, aircraft, and Pandora over land, while over water satellite, and to a lesser extent aircraft, retrievals underestimated TCNO2 particularly in the highly dynamic New York Harbor environment. Combined with model simulations, our shipborne measurements uniquely captured rapid transitions and fine-scale features in NO2 behavior across the New York City - Long Island Sound land-water continuum, driven by the complex interplay of human activity, chemistry, and local scale meteorology. These novel datasets provide critical information for improving satellite retrievals, enhancing air quality models, and informing management decisions, with important implications for the health of diverse communities and vulnerable ecosystems along this complex urban coastline.

Intraurban nitrogen dioxide (NO2) inequalities can be observed from space using the TROPOspheric Monitoring Instrument (TROPOMI). **Dressel et al. (2022)** use fine-scale airborne NO_2 remote sensing to demonstrate that daily TROPOMI observations resolve a major portion of census tract-scale NO_2 inequalities in the New York City–Newark urbanized area. They calculate daily TROPOMI NO2 inequalities over May 2018–September 2021, with disparities of 25–38% with race, ethnicity, and/or household income. They statistically analyze daily NO_2 inequalities, presenting empirical evidence of the systematic overburdening of communities of color and low-income neighborhoods with polluting sources, regulatory ozone co-benefits, and worsened NO_2 inequalities and cumulative NO_2 and urban heat burdens with climate change.

Dreesen et al. (2023) report on the NASA Ozone Water-Land Environmental Transition Study, 2018 (OWLETS-2) during which total non-methane hydrocarbons (TNMHC) and EPA PAMS Volatile Organic Compounds (VOCs) were measured on an island site in the northern Chesapeake Bay. TNMHC and VOCs were 2.1 and 3.4 times greater in concentration, respectively, than simultaneous measurements at a land site just 13 km away across the land–water interface. Measured chemical properties and patterns driven primarily by marine traffic sources over water during ozone conducive conditions were starkly different to immediately adjacent land sites, implying ozone abatement strategies over land may not be similarly applicable to ozone over the water.

The complex coastal land/water interface represents the convergence of multiple interdisciplinary scientific challenges such as the meteorology of the planetary boundary layer (PBL), air and water quality, and land surface gradients. **Sullivan et al. (2023)** define specific lingering issues with characterizing the land/water interface with current ground-based and spaceborne platforms, and reviews accomplishments from several NASA-supported field campaigns that aimed to advance our understanding of coastal regions. While current spaceborne observational platforms are limited in their ability to characterize the PBL and land/water interface, future polar-orbiting and geostationary platforms are likely to enable significant progress. They authors seek to motivate future concerted efforts to address remaining challenges for these complex and economically-important regions.

COVID-19 impacts on tropospheric composition and air quality

The COVID-19 pandemic led to the lockdown of urban centers worldwide, drastically perturbing the concentrations of global air pollutants. Peroxyacyl nitrates (PANs) are important photochemical pollutants formed from reactions between NO_x and volatile organic compounds (VOCs) and were substantially reduced during the pandemic. PAN products from SNPP- and JPSS-1 CrIS are being routinely produced and archived at the GES DISC under the Tropospheric Ozone and Precursors for Earth System Sounding (TROPESS) project. **Shogrin et al. (2023a)** used measurements from SNPP-CrIS and Aura-TES to quantify seasonal and interannual variability in PANs over the Mexico City Metropolitan Area (MCMA) and to identify prevalent spatial patterns of outflow from the city. **Shogrin et al. (2023b)** examined PAN measurements from SNPP-CrIS together with Aura-OMI NO_2 and HCHO over eight megacities: Mexico City, Beijing, Los Angeles, Tokyo, São Paulo, Delhi, Lagos, and Karachi. They find indicate that the large COVID-19-related reductions seen in NO_x and VOCs did not result in equally significant changes to PANs, suggesting the NO_x export potential of megacities was not reduced in this time.

Carbon monoxide

Carbon monoxide (CO) is a useful tracer of atmospheric pollution with direct emissions from incomplete combustion such as biomass and fossil fuel burning and secondary production from the oxidation of methane (CH_4) and volatile organic compounds (VOCs). **Worden et al. (2022)** have validated CrIS single field of view (FOV) retrievals of CO from the Tropospheric Ozone and Precursors for Earth System Sounding (TROPESS) project against a range of aircraft profile measurements. The comparison results provide confidence in the use of TROPESS/CrIS CO profiles and error characterization for continuing the multi decadal record of satellite CO observations that began with the MOPITT record. This study also demonstrates that the single FOV CrIS product provides improved representation of CO in smoke plumes compared to retrievals that combine multiple FOVs.

Yurganov and Rakitin (2022) used AIRS carbon monoxide observations to confirm an increase in both long-term trends and extremes of wildfire occurrence in the northern hemisphere over the last 20 years. Carbon monoxide is a product of biomass burning, closely related to significant greenhouse gas emissions from fires (CO_2, CH_4), and its observation from space can be used to study and monitor wildfires. The AIRS observations combined with a mass-balance model were used to estimate monthly amounts of CO emitted by fires and found to correlate closely with independently estimated CO emissions from the bottom-up Global Fire Emission Database. An overall an upward trend is found for the 20-year period (2002-2021), while the CO emissions fluctuate from year to year, and in some years (e.g., 2003, 2021) there are megafires that results in infrastructure damage and loss of life.

FIREX-AQ and wildfire impacts on air quality

Warnecke et al. (2022) reviewed the NOAA/NASA Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) experiment. This was was a multi-agency, inter-disciplinary research effort to: (a) obtain detailed measurements of trace gas and aerosol emissions from wildfires and prescribed fires using aircraft, satellites and ground-based instruments, (b) make extensive suborbital remote sensing measurements of fire dynamics, (c) assess local, regional, and global modeling of fires, and (d) strengthen connections to observables on the ground such as fuels and fuel consumption and satellite products such as burned area and fire radiative power. Measurements of western fires were made by the NASA DC-8 and two NOAA Twin Otter aircraft from Boise, ID, with the high-altitude NASA ER-2 deployed from Palmdale, CA to observe some of these fires in conjunction with satellite overpasses and the other aircraft. Further research was conducted on three mobile laboratories and ground sites, and 17 different modeling forecast and analyses products for fire, fuels and air quality and climate implications. From Salina, KS the DC-8 investigated 87 smaller fires in the Southeast with remote and *in situ* data collection. Sampling by all platforms was designed to measure emissions of trace gases and aerosols with multiple transects to capture the chemical transformation of these emissions and perform remote sensing observations of fire and smoke plumes under day and night conditions. The emissions were linked to fuels consumed and fire radiative power using orbital and suborbital remote sensing observations collected during overflights of the fires and smoke plumes and ground sampling of fuels.

Peterson et al. (2023) report on a unique and diverse set of *in situ* and remotely sensed measurements were obtained during FIREX-AQ before and during a pyrocumulonimbus (pyroCb) event over the Williams Flats fire in Washington State. This unique dataset confirms that pyroCb activity is an efficient vertical smoke transport pathway into the upper troposphere and lower stratosphere (UTLS). High-resolution remote sensing reveals that three plume cores linked to localized fire fronts, burning primarily in dense forest fuels, contributed to four total pyroCb "pulses." Cloud probe measurements and weather radar identify the presence of large ice particles within the pyroCb and hydrometers below cloud base, indicating precipitation development. The resulting feedbacks suggest that vertical smoke transport efficiency was reduced slightly when compared with intense pyroCb events reaching the lower stratosphere.

Tropospheric composition

Nowlan et al. (2023) describe new publicly available, multi-year formaldehyde (HCHO) data records from the Ozone Mapping and Profiler Suite (OMPS) nadir mapper (NM) instruments on the Suomi NPP and NOAA-20 satellites. They investigate the consistency of the OMPS products from Suomi NPP and NOAA-20 using long-term monthly means over 12 geographic regions, and also compare the products with publicly available TROPOMI HCHO observations. OMPS/Suomi-NPP and OMPS/NOAA-20 monthly mean HCHO vertical columns are highly consistent (r = 0.98), with low proportional (2%) and offset (2 × 1014 molecules cm−2) biases. OMPS HCHO monthly means are also well-correlated with those from TROPOMI (r = 0.92), although they are consistently 10% ± 16% larger in polluted regions (columns >8 × 1015 molecules cm−2), which result primarily from differences in air mass factors (AMF).

Despite recent progress, satellite retrievals of anthropogenic SO_2 still suffer from relatively low signal-to-noise ratios. **Li et al. (2022)** demonstrate a new machine learning data analysis method to improve the quality of satellite SO_2 products. Test results for 2005 show that the method can significantly reduce noise and artifacts over background regions. Over polluted areas, the monthly mean NN-analyzed and original slant column densities (SCD) generally agree to within ±15 %, indicating that the method can retain SO_2 signals in the original retrievals except for large volcanic eruptions. This is further confirmed by using the NN-analyzed SO_2 data for top-down emission estimates. Overall, the results presented here demonstrate that our new data analysis method can significantly improve the quality of existing OMI SO_2 retrievals.

Wasti and Wang (2022)) use satellite products to show that from 2005 to 2018, the HCHO column has been increasing in South Korea by 1.56 % per year during summer months, correlated with the increasing incidences of drought. HCHO increase is linked to higher ozone as most of South Korea is in the NOx-saturated or transitional regime.

Chang et al. (2023c) produce an improved percentile and seasonal (median) trend estimate of free tropospheric ozone above western North America (WNA), through a data fusion of ozonesonde, lidar, commercial aircraft, and field campaign measurements. They investigate the ozone variability based on a wide range of percentiles, comparing the ozone trends and variability above the California sub-domain to the full WNA region for better understanding of the correlations between different regional scales. In California, trends are clearly positive and stronger than over WNA. In contrast to increasing free tropospheric ozone, there are strong negative surface trends since 1995, with the greatest divergence found in summer.

Satellite retrievals of ammonia (NH_3)

Through its role as a precursor for fine particulate matter, atmospheric ammonia (NH3) can have negative impacts on both human health and ecosystem function. **Cady-Pereira et al. (2023)** evaluated NH3 observation from AIRS and CrIS against aircraft and surface measurements. They find that the satellite observations agree well with spatial and temporal variability seen in the reference measurements, and demonstrate that with oversampling, satellite NH3 measurements are strongly spatially correlated with the density of dairy farms within the small geographical extent of the Magic Valley region. **White et al. (2023)** show the benefit of joint use of CrIS and VIIRS in interpretation of satellite measurements of NH3 via improved information on the spatial extent of clouds in the CrIS field of view.

D. *Greenhouse gases, the carbon cycle and climate change*

ACFA supports research into the emissions and fluxes of CO_2, methane (CH_4) and nitrous oxide (N_2O) involving data from the two NASA Orbting Climate Observatories, OCO-2 and OCO-3. These observations also underpin observations and modeling of the carbon cycle by NASA-supported researchers. Highlighted here are ten papers on greenhouse gas emissions and the UN's Global Stocktake, with a particular focus on recent work on methane emissions.

GHG emissions, carbon inventories and the Global Stocktake

Accurate accounting of emissions and removals of CO_2 is critical for the planning and verification of emission reduction targets in support of the Paris Agreement. **Byrne et al. (2023)** present a pilot dataset of country-specific net carbon exchange (NCE; fossil plus terrestrial ecosystem fluxes) and terrestrial carbon stock changes aimed at informing countries' carbon budgets. These estimates are based on “top-down” NCE outputs from the v10 Orbiting Carbon Observatory (OCO-2) modeling intercomparison project (MIP), wherein an ensemble of inverse modeling groups conducted standardized experiments assimilating OCO-2 column-averaged dry-air mole fraction retrievals, *in situ* CO_2 measurements or combinations of these data. The v10 OCO-2 MIP NCE estimates are combined with "bottom-up" estimates of fossil fuel emissions and lateral carbon fluxes to estimate changes in terrestrial carbon stocks, which are impacted by anthropogenic and natural drivers. These flux and stock change estimates are reported annually (2015–2020) as both a global $1° \times 1°$ gridded dataset and a country-level dataset. These data provide capacity building support for nations unable to develop their own annual estimates and as a much-needed check for nations that refuse to report emissions.

Decreases in anthropogenic emissions of carbon dioxide during the COVID-19 pandemic provided the opportunity to demonstrate the capability of carbon monitoring systems to detect subtle, regional emissions changes. **Weir et al. [2022]** highlight the need to build on existing capabilities to establish quasi-operational greenhouse gas (GHG) modeling and data assimilation systems to provide independent verification of nationally reported emissions using atmospheric concentration observations. The advantages of a concentration-based monitoring system include improved spatial resolution and reduced impact of transport model errors, ability to support regional analysis and assessment of GHG and air quality co-benefits, and direct traceability to atmospheric observations. Results from COVID-19 demonstrate the opportunity as well as the limits on detectability imposed by uncertainty in land-atmosphere carbon dioxide exchange.

As policymakers seek to reduce carbon dioxide (CO_2) emissions, co-emitted species including nitrogen dioxide (NO_2) that are more readily observed offer promise in providing insights on emissions changes. **Yang et al. [2023]** demonstrate a method to estimate urban CO_2 emissions by using relationships between CO_2 and NO_2 observations from satellites, and then applying these relationships to NO_2 observations when corresponding CO_2 observations are unavailable, thereby generating NO_2-derived CO_2 fields. They first test the method using simulations of these gases for the cities of Buenos Aires, Melbourne, and Mexico City and demonstrate monthly variations that have previously not been observable using satellite CO_2 observations. Leveraging the larger quantity of available NO_2 observations will allow scientists to derive emissions estimates more frequently, helping to fill gaps in space-based CO_2 observations.

Quantifying the coevolution of greenhouse gases and air quality pollutants can provide insight into underlying anthropogenic processes enabling predictions of their emission trajectories. **Miyazaki and Bowman (2023)** classify the dynamics of historic emissions in terms of a modified Environmental Kuznets Curve (MEKC), which postulates the coevolution of fossil fuel CO_2($FFCO_2$) and NO_x emissions as a function of macroeconomic development. The MEKC broadly captures the historic $FFCO_2$-NO_x dynamical regimes for countries including the US, China, and India as well as IPCC scenarios. Given these dynamics, they find the predictive skill of FFCO2 given NO_x emissions constrained by satellite data is less than 2% error at one-year lags for many countries and less than 10% for 4-year lags. The proposed framework in conjunction with an increasing satellite constellation provides valuable guidance to near-term emission scenario development and evaluation at time-scales relevant to international assessments such as the Global Stocktake.

Using column CO_2 observations from OCO - 2 and - 3 missions on 10 occasions from March 2017-June 2022, **Nassar et al. (2022)** quantified CO_2 emissions from Europe's largest fossil fuel power plant, the Bełchatów Power Station in Poland. They found that the space-based CO_2 emission changes with a trend that is consistent with the independent reported hourly power generation trend that results from both permanent and temporary unit shutdowns. OCO-2 and OCO-3 emission estimates agree with the bottom-up emission estimates within their respective 1σ uncertainties for 9 of the 10 occasions. These results demonstrate the ability of OCO-2/3 missions to quantify emission reductions for a large facility, and their ability to quantify short-term emission changes to support verification of CO_2 emission reductions under Paris Agreement.

Methane emissions and fluxes

Large methane point sources exist across multiple source sectors (*e.g.*, oil, gas, coal, livestock, waste). Lacking is a robust assessment of the relative contribution of strong methane point sources against total or regional budgets, which is needed for prioritizing mitigation. **Cusworth et al. (2023)** flew airborne imaging spectrometers repeatedly over multiple basins in the United States to quantify large methane point sources across multiple sectors. They compared these point sources to satellite-based regional flux inversions and found that methane super-emitters consistently make up a sizable contribution to total the total flux in a basin. These results show that a significant climate benefit can be realized by specific isolation and remediation of relatively few sources.

Jacob et al. (2023) review the capability of current and scheduled satellite observations of atmospheric methane in the shortwave infrared (SWIR) to quantify methane emissions from the global scale down to point sources. They cover retrieval methods, precision and accuracy requirements, inverse and mass balance methods for inferring emissions, source detection thresholds, and observing system completeness. Satellite instruments are classified as area flux mappers of point source imagers, with complementary attributes. Current area flux mappers include GOSAT (2009–present), which provides a high-quality record for interpretation of long-term methane trends, and TROPOMI (2018–present), which provides global continuous daily mapping to quantify emissions on regional scales. Current point source imagers include the GHGSat constellation and several hyperspectral and multispectral land imaging sensors (PRISMA, Sentinel-2, Landsat-8/9, WorldView-3). Future area flux mappers, including MethaneSAT, GOSAT-GW, Sentinel-5, GeoCarb, and CO2M, will increase the capability to quantify emissions at high resolution, and the MERLIN lidar will improve observation of the Arctic. Expanding constellations of point source imagers including GHGSat and Carbon Mapper over the coming years will greatly improve observing system completeness for point sources through dense spatial coverage and frequent return times.

The 2015 Paris Climate Agreement and Global Methane Pledge formalized agreement for countries to report and reduce methane emissions to mitigate near-term climate change. Emission inventories generated through surface activity measurements are reported annually or bi-annually, and evaluated periodically through a "Global Stocktake." **Worden et al. (2023)** demonstrate a Bayesian, optimal estimation (OE) algorithm for evaluating a state-of-the-art inventory (EDGAR v6.0) using satellite-based emissions from 2009 to 2019. They find robust differences between satellite and EDGAR for total livestock, rice, and coal emissions f 14 ± 9, 12 ± 8, -11 ± 6 Tg CH_4/yr respectively. EDGAR and satellite agree that livestock emissions are increasing (0.25–1.3 Tg CH4/yr/yr), primarily in the Indo-Pakistan region, sub-tropical Africa, and the Southern Brazilian; East Asia rice emissions are also increasing, highlighting the importance of agriculture on the atmospheric methane growth rate. In contrast, low information content for the waste and fossil emission trends confounds comparison between EDGAR and satellite; increased sampling and spatial resolution of satellite observations are therefore needed to evaluate reported changes to emissions in these sectors.

Atmospheric methane mixing ratio rose by 15 ppbv between 2019 and 2020, the fastest growth rate on record. **Qu et al. (2023)** conduct a global inverse analysis of 2019–2020 Greenhouse Gases Observing Satellite observations of atmospheric methane to analyze the combination of sources and sinks driving this surge. The imbalance between sources and sinks of atmospheric methane increased by 31 Tg yr^{-1} from 2019 to 2020, representing a 36 Tg yr^{-1}forcing on the methane budget away from steady state. 86% of the forcing in the base inversion is from increasing emissions, and only 14% is from decrease in tropospheric OH. Half of the increase in emissions is from Africa (15 Tg yr^{-1}) and appears to be driven by wetland inundation. There is also a large relative increase in emissions from Canada and Alaska (4.8 Tg yr^{-1}, 24%) that could be driven by temperature sensitivity of boreal wetland emissions.

Offshore oil and natural gas platforms are responsible for about 30% of global oil and natural gas production, yet few studies that have directly measured atmospheric methane emanating from these platforms. In 2021, the Global Airborne Observatory platform, an aircraft equipped with a visible shortwave infrared imaging spectrometer, surveyed over 150 offshore platforms and surrounding infrastructure in US federal and state waters in the Gulf of Mexico. Using glint targeting, **Ayasse et al. (2023)** mapped the CH_4 emissions and show that emissions from the measured platforms exhibit highly skewed super-emitter behavior. These emissions mostly come from tanks and vent booms or stacks. They also find that the persistence and the loss rate from shallow-water offshore infrastructure tends to be much higher than for typical onshore production.

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. We highlight in this section eight papers covering the topics of deep convection and transport, the effects of the eruption of the Hunga Tonga-Hunga Ha'apai volcano, the effects of smoke in the stratosphere from pyrocumulonimbus, and trends in ozone profiles.

Deep convection, stratosphere-troposphere exchange and tracer transport

During northern summer, flow in the upper troposphere and lower stratosphere over North America is characterized by a large-scale anticyclone. **Chang et al. (2022b)** used data from the Next Generation Weather Radar and the ERA5 reanalysis to locate tropopause-penetrating overshooting convection (OC) during May–August of 2008–2020. Evidence of convective transport is found well above the 380 K isentrope, which is the top of the "lowermost stratosphere". Trajectory calculations indicate that July exhibits the strongest confinement of outflows from OC within the anticyclone, and given sufficient injection height, convective injection south of the jet and/or into anticyclonic regimes increases the chances of air remaining in the stratosphere. After 30 days, 45% of all air masses injected above the tropopause remain in the global stratosphere.

In a modeling study, **Ueyama et al. (2023)** estimate the overall impact of deep convection on global stratospheric humidity and find that over the 2006-2016 period convection moistened the lower stratosphere by about 10% in boreal winters and summers with smaller year-to-year variations. While deep convective cloud tops that penetrate into the lower stratosphere have a relatively small effect on stratospheric water vapor, convection still moistens the lower stratosphere by transporting humid air laden with numerous ice crystals to the tropical uppermost troposphere, just below the stratosphere. Some of this humid air subsequently ascends into the stratosphere and ultimately increases the humidity of the lower stratosphere.

Tinney et al. (2022) devise a novel definition of the tropopause based of the vertical gradient of potential temperature. Balloon-borne ozone and water vapor observations demonstrate that the new potential temperature gradient tropopause better distinguishes tropospheric and stratospheric composition compared to traditional tropopause definitions such as the temperature lapse rate. The new definition is also applicable for the entire globe, whereas traditional tropopause definitions are typically best suited for specific latitudinal regions. It is easy to compute, requires only vertical profiles of potential temperature, and is superior for studies of atmospheric composition.

Impacts of the eruption of Hunga Tonga-Hunga Ha'apai on stratospheric composition

With observations from the Ozone Mapping Profiler Suite – Limb Profiler (OMPS-LP), **Taha et al. (2022)** show that the eruption of the Hunga Tonga-Hunga Ha'apai (HT) submarine volcano on January 15, 2022 lofted materials to a record-breaking altitude of ~58 km, and within two weeks injected material between 20–30 km altitude had circulated the globe. The estimated stratospheric aerosol optical depth (sAOD) is the largest since the Pinatubo eruption and is at least twice as great as the sAOD after the 2015 Calbubo eruption despite the similar SO_2 injection from that eruption. While the main aerosol layer remained trapped in the tropical pipe through June, small parts had already made it to both the Northern and Southern Hemisphere poles by April.

The eruption of Hunga Tonga in January 2022 injected an amount of water vapor into the stratosphere that is unprecedented in the satellite era. In the ensuing months Aura Microwave Limb Sounder (MLS) measurements showed that this plume of water vapor spread from its original injection site at 20.5°S to Mauna Loa, Hawaii at 19.5°N, where **Nedoluha et al. (2023)** found an increase in April by the ground-based Water Vapor

Millimeter-wave Spectrometer instruments. The sudden increase in H_2O with the arrival of the HT plume over Mauna Loa came on top of H_2O mixing ratios that were already higher than normal due to the Quasi-Biennial Oscillation (QBO).

Schoeberl et al. (2022) find that after the HT eruption, distinct aerosol and water vapor layers formed in the tropical Southern Hemisphere (SH) stratosphere, with the water vapor layer slightly displaced above the aerosol layer at 26 km. A cold temperature anomaly formed in association with the water vapor layer at about 25 km due to enhanced radiative cooling. Measurements following the eruption show that the water vapor layer was slowly rising while the aerosol layer was descending, which is consistent with the understanding of tropical stratospheric dynamics.

The HT eruption injected a relatively small amount of SO_2 but significantly more water into the stratosphere than previously seen in the modern satellite record. **Zhu et al. (2022)** show that the large amount of water resulted in large perturbations to stratospheric aerosol evolution. Their climate model simulation demonstrates that this additional source of water vapor increases hydroxide, which halves the sulfur dioxide lifetime. Subsequent coagulation creates larger sulfate particles that double the stratospheric aerosol optical depth.

Stratospheric ozone trends

Godin-Beekman et al. (2022) present an updated evaluation of stratospheric ozone profile trends in the 60° S–60° N latitude range over the 2000–2020 period using an updated version of the Long-term Ozone Trends and Uncertainties in the Stratosphere (LOTUS) regression model that was used to evaluate such trends up to 2016 for the last WMO Ozone Assessment (2018). They confirm past results showing an ozone increase in the upper stratosphere, which is now significant in the three broad latitude bands. The increase is largest in the Northern and Southern Hemisphere midlatitudes, with ∼2.2 ± 0.7 % per decade at ∼2.1 hPa and ∼2.1 ± 0.6 % per decade at ∼3.2 hPa respectively compared to ∼1.6 ± 0.6 % per decade at ∼2.6 hPa in the tropics. New trend signals have emerged from the records, such as z significant decrease in ozone in the tropics around 35 hPa; downward trends in the lower tropical stratosphere are not significant. Observed negative trends in the lower stratosphere are not reproduced by models at southern and, in particular, at northern midlatitudes, where models report an ozone increase, but both measured and modeled trend uncertainties are quite large.

E. Research aircraft campaigns and ground-based networks supported by ACFA

NASA's Tropospheric Emissions: Monitoring of POllution (**TEMPO**) mission was launched on April 7, 2023 from Cape Canaveral, Florida. With first light at 11:15 AM EDT on August 2, TEMPO is now providing geostationary observations of air quality across North America on an hourly basis during the day.

The **S**ynergistic **T**EMPO **A**ir **Q**uality **S**cience (**STAQS**) mission took place in July and August 2023, integrating the early TEMPO satellite observations with traditional air quality monitoring with the goal understanding of air quality science and increasing societal benefit. STAQS targeted domains in Los Angeles, Chicago and New York City and several secondary domains across North America with ground and airborne based measurements.

The Atmospheric Composition Focus Area provides support to a broad range of ground-based observational networks, both domestic and worldwide. In addition to AGAGE and SHADOZ, these include the Network for Detection of Atmospheric Composition Change (NDACC), the Aerosol Robotics Network (AERONET), the MicroPulse Lidar Network (MPLNet), the Total Carbon Column Observing Network (TCCON), the Pandonia Global Network (PGN), and the Tropoospheric Ozone Lidar Network (TOLNet). These networks continue to monitor key atmospheric trace constituents and provide critical validation for satellite-based measurements, despite a few lingering challenges to operations from the COVID pandemic.

F. Development and coordination of satellite observing systems and international partnerships: ACFA contributions to the CEOS AC-VC and NASA ESO/AOS

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. AC-VC chairs from ESA, NASA, and NIES-Japan, as well as many NASA researchers lead and participate in its diverse activities. The CEOS AC-VC team, which ACFA co-chairs, is drafting a white paper entitled "Monitoring Surface PM2.5: An International Constellation Approach to Enhancing the Role of Satellite Observations", the latest draft of which was produced in September 2022.
The NASA Atmospheric Observing System (AOS) will make observations of aerosols and of clouds, convection and precipitation, two of the five Designated Observables identified in the 2017 Earth Science Decadal Survey from the National Academy. AOS is one of four satellite systems currently in formulation that comprise the core of the NASA Earth Science Observatory (ESO). ACFA Headquarters personnel are Program Scientists for AOS.

Section 1.1.8.2 Carbon Cycle and Ecosystems Focus Area

The Carbon Cycle and Ecosystems focus area conducts research that is critical for further understanding the Earth System and its components and characterize human-induced forcings from those that are naturally occurring. The focus area's research spans the land and water, and covers a variety of spatial scales, from local and regional to global. In order to achieve this, a wealth of in situ, airborne and satellite observations, as well as modeling approaches, are utilized to further the understanding of Earth's ecosystems and biogeochemical cycles, and improve the algorithms and products developed from these observing approaches. Selected research results and other accomplishments of the 2022 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 the vulnerability and resilience of aquatic and terrestrial ecosystems, including ecosystem shifts in response to climate extremes and human impacts, changes in forest structure, their impact on life's biogeography, and their ability to further sequester carbon and support biodiversity, continued shifts in the Arctic-Boreal ecosystems and the implications for greenhouse gas emission/sequestration, changes in the wildland-urban interface, and the need for improved characterization of episodic events, which in the future may increase in frequency.

Ocean Biology and Biogeochemistry

Coastal resilience and improving resource management

Changes in the coastal environment are fast paced; these interface regions are highly dynamic and harbor a number of critical ecosystem services. These are also highly populated areas that are impacted by several natural and anthropogenic forcings, and more than ever satellite-based Earth observations are critical to understanding and predicting the rapid changes coastal environments are undergoing. Schaefer et al (2022) provided examples of the usefulness of commercial, high-resolution data from PlanetScope passive satellites to detect surface oil in the Gulf of Mexico and their potential use at other locations in continental U.S., Hawaii, and northern latitudes, including Alaska. Louis and colleagues (2023) explored whether the red solar induced fluorescence (SIF) from the TROPOspheric Monitoring Instrument (TROPOMI) could be used to detect harmful algal blooms such as *Karenia brevis*. The authors confirmed that SIF from TROPOMI, designed for atmospheric measurements, can be utilized for HAB detection under severe bloom conditions in variable cloud and aerosol conditions, providing nearly double the amount of spatiotemporal fluorescence information than traditional methods using sensors such as MODIS. These novel approaches, combined with other existing and planned satellite missions, including NASA's Geostationary Littoral Imaging and Monitoring Radiometer (GLIMR), can increase the coverage and provide high temporal images of areas affected by episodic events that require quick action. Other important applications of satellite remote sensing for improved coastal ecosystem management include mapping and monitoring of blue carbon ecosystems such as seagrasses, which are notoriously difficult to measure. Coffer et al. (2023) leveraged Maxar's WorldView-2 and WorldView-3 satellites and demonstrated their suitability and accuracy for mapping and classifying seagrasses at 11 study areas across the continental United States, representing geographically, ecologically, and climatically diverse regions. The authors developed an operational approach for mapping these blue carbon ecosystems at national and global scales, which is a significant leap to the use of high resolution satellite imager as a management tool to complement field- and aerial-based mapping efforts for monitoring seagrass ecosystems. Marine debris has become a pervasive issue and in particular in coastal areas where most debris enters the ocean. Active research continues to evaluate the use of satellite observations in the detection and tracking of marine debris in the ocean; for example, Hu et al. (2023) examined the usefulness of a number of remote sensing and optical techniques to quantify and identify marine debris that entered the northern Gulf of Mexico following Hurricane Katrina in 2005. The authors show that the debris was likely dominated by driftwood, dead plants (e.g., uprooted marsh) and plastics and other man-made materials. The authors were further able to calculate, for the first time, the extent and transport of a hurricane-derived debris plume, which can provide important information for mitigation of ecological impacts post disaster.

Impact of climate change on aquatic ecosystems
With more frequency, impacts of climate change are being observed on aquatic ecosystems. Mutli-decade sustained in situ and satellite observations are critical to distinguish natural vs. anthropogenic drivers of change, and to better understand and predict future ecosystem shifts. Cael et al. (2023) exemplify the importance of sustained ocean observations by using 20 years of continuous Earth-observing satellite data to detect trends in ocean color, a proxy of
surface ocean ecosystems. On average, low-latitude oceans have become 'greener' in the past 20 years. The authors suggest that these trends are not solely related to temperature changes, but also to changing mixed layer depth or upper ocean stratification, which are known to affect plankton community structure and biomass. They further note that the changes identified have potential implications both for the role of plankton in marine biogeochemical cycles and ocean carbon storage, and for plankton consumption by higher trophic levels and thus fisheries.

Arteaga and Rousseaux (2023) examined the implications of MHW on phytoplankton populations in the Pacific ocean, in particular focusing on two of the most prominent events (the 2013-2014 "Blob," which affected the Gulf of Alaska, and the 2016 El Niño, which was one of the most extreme ENSO events ever recorded in the Tropical Pacific). They found that there was a marked decline in diatoms, a species of phytoplankton that a number of species depend on, and that this decline was caused by a strong reduction in the upwelling of nitrate-rich deep-water. Upwelling changes were caused by diminished wind intensity over the equatorial Pacific during the strong 2016 El Niño. Lower nutrient concentrations favored the growth of smaller phytoplankton, which outcompeted other groups in growth and productivity. The authors conclude that these changes in community composition may become the norm in a high ocean temperature world. Polar ecosystems have been at the forefront of ecological changes due to climate change, one of the most notable impacts being the changes in the timing of plankton blooms. Manizza et al. (2023) utilize the ECCO2-Darwin ocean biogeochemistry model to gain a mechanistic understanding of how changes in sea-ice seasonality impact the phenology of Arctic Ocean phytoplankton blooms. While earlier bloom initiation is observed and attributed to earlier sea ice melt, their results show that the heterogeneity in duration across the Arctic Ocean is linked to nutrient availability and temperature. These changes in timing and duration of plankton blooms in the Arctic are anticipated to have consequences for higher trophic levels. This would also have consequences for oceanic carbon uptake at high latitudes.

Spaceborne imaging spectroscopy can not only provide estimates of plant abundance at a global level, but also provide information on its physiological condition; this is important because it can provide information that will enable the prediction of how plant populations will respond to environmental change. Bell and Siegel (2023) utilize remote sensing observations to assess the abundance and health of giant kelp, an important ecosystem-structuring species, at regional and local scales. The authors found that both extrinsic and intrinsic processes regulate population dynamics but on different spatial scales; this information is important for predicting future kelp health, especially with increase in ocean temperature and decreased nutrient inputs.

Pushing the boundaries of satellite observations for novel applications

Continuing to identify observational gaps that can be addressed with satellite remote sensing and developing the necessary technology and algorithms to address these gaps is critical to improve our understanding of the Earth system and how it is interconnected. This is particularly true for episodic events, most of which are poorly characterized and accounted for in our current understanding of the Earth System. Bisson et al. (2023) examined the applicability of remote sensing for the observation of volcanic ash deposition events in coastal areas, including their impacts to ecosystems, and identified key considerations for future research in this area; the authors stress the need for a robust atmospheric correction, especially under challenging conditions such as the ones surrounding eruptions, where ash plumes introduce strongly absorbing aerosols into the atmosphere, conditions under which the standard ocean color atmospheric correction methods are not as accurate. The authors further point out the need to move from a single sensor to a multi-sensor approach, combining both passive and active technologies to improve multidisciplinary observations of these events, and coupling these observations with models to extract more information than what is available from satellite data alone. D’sa et al. (2023) provided a review of current remote sensing observational capabilities of extreme events and disturbances, and their impacts on aquatic carbon cycling at multiple spatiotemporal scales particularly in the coastal zone. Their review highlighted the challenges in quantifying carbon cycling across the coastal interface and identified necessary technologies for the advancement of carbon cycling research in the coastal zone, including modeling and algorithm development, leveraging upcoming hyperspectral missions such as PACE, SBG, and GLIMR.

As has been noted, further developing approaches that can exploit the optical information in remote sensing images is the foundation to furthering aquatic satellite applications. Stramski et al. (2023) demonstrated that, using the ratio of particulate organic carbon to suspended particulate matter concentration, they were able to estimate water quality of a number of western Arctic seas that exhibit a broad range of water composition and optical properties. Arctic waters are notoriously optically-complex, and their novel approaches have broader applicability across a wide range of water bodies. Similarly, Zhang et al.

(2023) utilized particle size distribution to estimate mass and carbon fluxes in the Northeast Pacific Ocean as part of the work funded under EXPORTS. These estimates lay the foundation of approaches that can be used to validate spaceborne lidar measurements.

Terrestrial Ecology

Remote Sensing of Forest Structure and Function

Remote sensing of forest structure and function is key to improving our understanding of the global carbon cycle as well as the potential feedbacks of terrestrial carbon to the atmosphere. One novel and powerful tool that is providing groundbreaking information on forest structure is NASA's Global Ecosystem Dynamics Investigation (GEDI). GEDI is a spaceborne lidar hosted on the International Space Station (ISS) that was designed to retrieve vegetation structure within a theoretical sampling design that explicitly quantifies aboveground biomass (AGB) and its uncertainty across a variety of spatial scales. Dubayah et al. (2022) provided a detailed description of the GEDI mission and present estimates of mean AGB densities at 1 km resolution across the entire GEDI domain (latitudes 51°N to 51°S). They also provided AGB estimates aggregated to the national level for every country GEDI observes, and at the sub-national level for the United States. Bruening et al. (2023) examined the biases in comparing biomass estimates using GEDI's hybrid estimation framework with estimates from the US Forest Service's Forest Inventory and Analysis (FIA) program. They identified two issues impacting GEDI's estimation process: incomplete filtering of low-quality GEDI observations and regional biases in GEDI's footprint-level biomass models. Breuning et al (2023) developed a solution to each, i.e., improved data filtering and GEDI-FIA fusion models that were more compatible with GEDI's hybrid estimation approach. These improved models predicted realistic distributions of AGB, with equal or improved performance relative to GEDI's standard L4A models for all regions. The authors then produced GEDI-FIA fusion estimates that were more precise than the FIA estimates and resulted in a bias reduction of 86.7% relative to the original GEDI estimates. This work is an important step toward achieving reliable baseline forest carbon stocks and provides a viable methodology for training remote sensing biomass models.

Other important applications of GEDI data include analyzing the effectiveness of protected areas (PA) for carbon sequestration. Establishing PAs represents an effective and important approach to forest conservation, but their contribution to climate change mitigation was largely unquantified. Duncanson et al (2023) used ~412 million GEDI lidar samples to estimate carbon sequestration in PAs, concluding that a total of ~19.7 Gt of additional AGB are associated with PA status. These higher carbon stocks are roughly equivalent to annual global fossil fuel emissions. The total measured PA AGB was ~125.3 Gt, 26% of all terrestrial woody AGB mapped by GEDI globally. These results underscore the importance of conservation of high integrity, high biomass forests for avoiding carbon emissions and preserving future sequestration. Indeed, Liang et al. (2023) found that in Tanzania all analyzed PAs possess ~24% higher AGB than their unprotected counterparts. Community-governed PAs were the most effective category of PAs at preserving forest structure and AGB – often out-performing those managed by international or national entities. In addition, PAs designated under more than one entity performed better than the PAs with a single designation, especially those with multiple international designations. This country-scale methodology for using GEDI data to quantify and compare forest structure and AGB in PAs relative to unprotected areas can be readily applied to other regions and countries to assess the effectiveness of both protecting forest ecosystems and facilitating carbon storage.

Combining GEDI data with other spaceborne lidar observations also has the potential to further advancing carbon modeling at a global scale. For example, Ma et al. (2023) used novel remote sensing observations of tree canopy height collected by GEDI and ICESat-2 together with a newly developed global Ecosystem Demography model (v3.0) to characterize the spatial heterogeneity of global forest structure and quantify the corresponding implications for forest carbon stocks and fluxes. At 0.25° to 0.01° resolution, process-based models were able to capture detailed spatial patterns of forest structure previously unattainable, including patterns of natural and anthropogenic disturbance and recovery. This work is a key step to the development of a global forest carbon monitoring and modeling system that integrates information on forest structure.

Choi et al. (2023) provide a demonstration of how GEDI waveform data can be combined with interferometric coherence data from the TanDEM-X satellites to provide accurate, wall to wall, maps of forest height at regional to global scales. The authors developed a 25 m forest height map for the entire island of Tasmania, which was validated against an airborne lidar survey of the area. This work demonstrated how data fusion can be used to transform the spatial sampling of GEDI into continuous maps and provides a framework for conducting data fusion with other satellite sensors.

Understanding the vertical stratification of tropical forests is important because a majority of the world's animal species inhabit tropical forest canopies. Doughty et al. (2023) analyzed ~55 million GEDI 25m diameter footprints in tropical forests and found that the most common type of forest structure showed a one-peak waveform, indicating no vertical stratification. The authors did note that there are geographic gradients of canopy stratification within the Amazon basin, SE Asia, and Africa, i.e., some areas had greater canopy stratification than others. The number of canopy layers was significantly, but weakly, correlated with tree height and forest biomass. More broadly, areas having lower fertility or higher temperatures were associated with shorter, less stratified forests with lower biomass.

Vulnerability and Resilience of Northern Ecosystems to Environmental Change
NASA's Terrestrial Ecology Program continues to support the Arctic-Boreal Vulnerability Experiment (ABoVE), a ten-year field and modeling effort focused on Arctic ecosystems. ABoVE is currently in its last phase (Phase 3, 2022-2026), which focuses on synthesis studies and filling critical research gaps that remain from its previous two phases. Over the duration of ABoVE, our understanding of the changing Arctic-Boreal regions has been significantly improved, in particular the understanding of climate change impacts on greenhouse gas exchange at high latitudes and ecosystem vulnerability to increasing temperatures. For instance, the enhancement in methane (CH_4) hotspots adjacent to beaver ponds is an example of a new disturbance regime that is accelerating the effects of climate change in the Arctic. As beavers continue to expand into the Arctic due to increasing

temperatures, and reshape lowland ecosystems, continued wetland creation, permafrost thaw, and alteration of the Arctic carbon cycle can be expected. Using the AVIRIS NG airborne hyperspectral sensor, Clark et al. (2023) examined the spatial relationships of CH_4 hotspots for 118 beaver ponds in Alaska that were within 30 m of waterbodies. The authors found that there was a 51% greater CH_4 hotspot occurrence around beaver ponds relative to nearby non-beaver waterbodies, and that these occurrences also extended beyond the ponds to a distance of 60 m.

Changes in Arctic temperature have also exacerbated wildfires in the Arctic-Boreal region; fire is the dominant disturbance agent in Alaskan and Canadian boreal ecosystems and releases large amounts of carbon into the atmosphere. To track the spatiotemporal changes in burned area and fire carbon emissions over time, Potter et al. (2023) developed a new burned-area detection algorithm for the period 2001–2019 across Alaska and Canada at 500 m resolution that utilizes finer-scale 30 m Landsat imagery to account for land cover unsuitable for burning. The authors also developed statistical models to predict burn depth and carbon combustion for the ABoVE Study Area. They estimated that 2.37 Mha burned annually between 2001–2019 over the ABoVE domain, emitting roughly 79.3 Tg of carbon per year. The years 2005, 2014 and 2015 were particularly high fire years for area burned. Potter et al. (2023) also found larger-fire years and later-season burning were associated with greater mean combustion.

Land Cover and Land Use Change

Trees Outside Forests and Biomass

The distribution and characteristics of dryland trees, including density, cover, size, mass, and carbon content, remain poorly understood at larger scales such as sub-continental to continental levels. However, this information is crucial for ecological protection, carbon accounting, climate mitigation, and restoration efforts in dryland ecosystems. In a recent study, Tucker et al. (2023) assessed over 9.9 billion trees in semi-arid sub-Saharan Africa, using a combination of field data, machine learning techniques, satellite data, and high-performance computing. They attributed wood, foliage, and root carbon to each tree within the 0–1,000 mm/yr rainfall zone. The study revealed significant variations in individual tree carbon stocks, ranging from 0.54 Mg C ha^{-1} and 63 kg C $tree^{-1}$ in arid zones to 3.7 Mg C ha^{-1} and 98 kg $tree^{-1}$ in sub-humid zones. The team's total estimate of 0.84 Pg C for their study area is important due to previous model inaccuracies. This benchmarking can enhance carbon cycle understanding and address land degradation concerns. In another study, using the Planetscope nanosatellite constellation, Reiner et al. (2023) reported that more than one quarter of Africa's tree cover exists outside previously classified forest areas. Further, Mugabowindekwe et al. (2023) proposed an innovative approach to map individual tree carbon stock in Rwanda using aerial photography. They found that 72% of trees were in farmlands and savannas, with 17% in plantations, contributing to 48.6% of the national aboveground carbon stocks. Natural forests covered 11% of trees but accounted for 51.4% of the national carbon stocks. These studies have significant implications for conservation efforts, carbon accounting initiatives, climate change mitigation strategies, and restoration projects in dryland ecosystems.

Forest degradation and biomass changes

Tropical forests play a vital role in the global carbon budget, but they are threatened by deforestation and forest degradation due to various factors like fire, selective logging, and fragmentation. Rangel Pinagé et al. (2023) used textural metrics from PlanetScope images to implement a probabilistic classification framework and identify intact, logged, and burned forests in three Amazonian sites. Biomass estimates were also calculated using airborne lidar. The classification approach achieved an overall accuracy of 0.86, with variations across individual sites. Logged forests showed varying biomass changes, while burned forests experienced an average carbon loss of 35%. The study highlighted that increased uncertainty in forest degradation classification also lead to increases in uncertainty of biomass estimates. Overall, the study pointed out the importance of accounting for uncertainty when attributing biomass changes to forest degradation categories. The results hold significance for national greenhouse gas inventories and contribute to an enhanced comprehension of forest degradation on carbon stocks in the Amazon.

Wildland Urban Interface (WUI) and Vegetation Fires

The wildland-urban interface (WUI) refers to the area where human development and infrastructure meet or intermingle with natural wildland areas. WUI maps identify areas with wildfire risk, but they are often outdated owing to the lack of building data. In a recent study, Kasraee et al. (2023) used convolutional neural networks (CNNs) to detect buildings in the WUI for wildfire risk assessment. The researchers used a CNN-based building dataset and a CNN model in conjunction with National Agriculture Imagery Program (NAIP) imagery with 0.6- meter resolution to identify buildings pre- and post-wildfire for three California wildfires. The results showed moderate accuracies for detecting buildings, with severe underestimation in areas where trees obscured buildings. The CNN model performed better post-fire, with accuracies ≥73%. The study reveals CNN limitations in WUI mapping and stresses the need for accuracy improvements in wildfire risk assessment. The first European high-resolution map of the Wildland-Urban Interface was recently developed by Bar-Massad et al. (2023), who found that the WUI covers about 7.4 % of the European area, varying considerably within and among countries, and is significantly related to various socio-economic and demographic factors. The new WUI map can aid local and regional wildfire risk management, ecological assessments, policy, and decision making.

One of the significant impacts of vegetation fires is air pollution. The work by Vadrevu et al. (2023), which centers on vegetation fires and pollution, is gaining considerable attention and recognition in both Asia and the US. The book encompasses a broad spectrum of fire-related subjects, such as mapping, monitoring, greenhouse gas emissions, and air pollution modeling across South and Southeast Asia. The book's broad appeal stems from its valuable and diverse approach to fire management and its environmental consequences. The chapters underscore the following points: Air pollutants emitted from fires can circulate regionally and settle far from their origins, as observed with Indonesian fire emissions reaching Singapore, Malaysia, Brunei, and southern Thailand. The notable transboundary nature of these pollutants has led to adverse impacts on air quality and public health. Addressing small fires from crop residue burning is vital due to their greenhouse gas contributions. Monitoring subsurface peatland smoldering fires demands advanced remote sensing and creative algorithms due to their below-ground occurrence and smoke's signal interference. It is imperative to integrate satellite data and ground-based measurements to establish input parameters using cutting-edge AI and Deep Learning for fire behavior prediction. One of the priorities identified includes creating Decision Support Systems (DSS) for mapping, monitoring, and assessing fire impacts in the region.

Land-Use Hotspots in Central Asia

Land use hotspots are specific areas or regions with high levels of land-use activities, such as urban development, agricultural expansion, deforestation, and other land-use changes with high impact on society. In a study by Yuan et al. (2022), the authors quantified the direction, extent, and spatial variation of land-cover change over three decades (1990-2020) at three administrative levels in Kazakhstan and Mongolia using Landsat data and random forests classifier. The research findings revealed that grasslands dominate the vast steppe landscapes in both countries. Notably, Kazakhstan experienced higher rates of land-cover change over a larger land area compared to Mongolia. The most common land-cover conversion observed was from grassland to cropland, reflecting past agricultural development campaigns in the region. The study highlights the influence of policy decisions and shifts on the formation and expansion of land-use hotspots.

Biodiversity and Ecological Conservation

Distribution and Abundance of Organisms

The distribution and abundance of organisms and the condition of the ecosystems they comprise represent vitally important information, whether one seeks fundamental understanding of life's biogeography or to develop forecasting tools to conserve life on Earth during a human-driven mass extinction event. The development of indicators to rapidly identify ecosystem change has been an important tool for ecosystem management; satellite imagery and associated models are rapidly increasing the power of such indicators, expanding the understanding of organism distribution and habitat utilization. Schroeder et al. (2022) developed a new indicator, the Habitat Compression Index (HCI), which is focused on upwelling systems, regions characterized by intense seasonal productivity that support important fisheries. The HCI uses satellite observations and models to track highly productive "cool-water thermal habitats" in upwelling systems and provides information on when there may be habitat compression, which can have severe impacts on pelagic biodiversity and ecosystem function. The HCI is expected to also inform of potential ecosystem shifts in coastal upwelling systems and the fisheries they support, better preparing managers. Razenkova et al. (2023) used two sets of habitat indices derived directly from the remote sensing of vegetation productivity (Dynamic Habitat Indices or DHIs) and snow/frozen ground (Winter Habitat Indices or WHIs), along with other factors, to estimate population densities for eight mammal species across Russia from 1981 to 2010. Similarly, Keyser et al. (2023) used WHIs, in concert with approximately 2.8 million citizen science observations from eBird, to quantify how snow cover dynamics drive overwintering bird distributions across the U.S. and found both snow association and snow avoidance to be strong predictors of species distributions. In essence, snow serves as an ecological filter for bird ranges.

The reliance on satellite data for natural resources managers in coastal regions continues to increase; the broad perspective and frequent data coverage which enables time series analyses of change in this dynamic region are critical to improve management of resources and prepare communities for change. For example, Suca et al. (2022) developed a species distribution model for the distribution and abundance of market squid (*Doryteuthis opalescens*) - an important California fishery species, utilizing in situ data and chlorophyll and temperature data from various satellites. The authors found that sea surface temperature and upwelling dynamics were linked to juvenile market squid abundance and recruitment; changes in these environmental factors also contributed to the northward range expansion of market squid. The authors underscore the importance of understanding distribution of market squid as it is an economically and ecologically critical species. Wethington et al. (2023) explored, using passive microwave sea ice satellite imagery, Landsat imagery, aerial drones, and in-situ surveys, the distribution and abundance of Adelie penguins (*Pygoscelis adeliae*) in the West Antarctic Peninsula on both sides of its "Adelie gap" feature—a 400 km stretch in which there are no Adelie penguin colonies but there are colonies of congeneric Gentoo penguins (*Pygoscelis papua*). Contrary to the assumption that Adelies are in significant decline throughout the entire Peninsula, the authors documented flourishing populations of Adelies and Gentoos northeast and northwest of the so-called Adelie gap. Its findings further support the existence of two separate and geographically distinct populations of Adelie penguins and include calls for implementation of conservation measures northeast-of-gap, an area of high value for maintaining the species.

Vegetation Structure for Biodiversity Understanding and Conservation

The confluence of the NASA Ice, Cloud and land Elevation Satellite-2 (ICESAT-2) lidar mission and its Global Ecosystems Dynamics Investigation (GEDI) International Space Station lidar with the European Space Agency's Sentinel-1 radar missions results in a vast amount of space-based vegetation structure data. Since Robert MacArthur's pioneering work in the 1950s, the importance of vegetation structure for defining species habitats through its support of a number of vital behaviors has become clear. Russo et al. (2023) completed this circle of knowledge by first reviewing examples documenting how vegetation structure influences animal behaviors followed by examples of how animal activities directly and indirectly influence vegetation structure. They noted the critical role passive and active remote sensing, in combination with animal tracking data, play in not only capturing but also quantifying this feedback loop between vegetation structure and animal behaviors. The authors point out that there is still a lot of work to be done in this area, in particular in understanding the feedback loops between animal interactions and vegetation structure; this is critical to better conserve ecosystems that face major challenges due human activities and climate change. Killion et al. (2023) derived structural diversity from GEDI products for use with camera trap photographs to build species occupancy models for seven species of herbivores and carnivores practicing a variety of feeding strategies. The GEDI 3D habitat structural variables had the strongest overall effects in estimating the occupancy of the focal mammals in the study. In combination with in-situ biodiversity data (e.g., animal telemetry and camera traps), vegetation structural data from satellites increases the predictive power of distribution models.

Protected areas (PAs), such as national parks and nature reserves, are viewed as critical to slow the global loss of biodiversity; as such, assessing the efficacy of PAs in conservation is critical. Many of the existing PAs exist in remote areas, making satellite observations critical for such assessment. Brodie et al. (2023) assessed the efficacy of terrestrial PAs for conserving tropical mammal and bird diversity in Southeast Asia inside and outside their boundaries, while taking into account accessibility of the PA, and 3D forest structure using GEDI. The authors found that PAs not only increased vertebrate diversity within its limits, but enhanced diversity in the adjacent unprotected landscape. The authors conclude that ambitious goals such as those of the United Nations '30 x 30 goal' would result in enhanced environmental and biodiversity benefits for the broader landscape.

Human Impacts on Biodiversity and its Conservation

Human actions are behind growing losses in biodiversity globally, resulting in an ongoing phenomenon comparable to the five mass extinctions in the geologic record. Four key anthropogenic drivers of biodiversity loss are habitat loss through land use, pollution, climate change, and invasive species. Successful conservation depends upon improved understanding of these drivers of loss such that we can forecast the impacts of human actions ahead of further declines. Binley et al. (2023) explored, using eBird citizen science products and MODIS land cover, the impacts of converting forests to agriculture on 238 forest bird species in North America through the lens of three traits: migratory strategy, dietary guild, and foraging strategy. They found that impacts on the birds varied according to the traits of the bird species. For example, insectivores and bark foragers were strongly and negatively affected by agriculture and thus need the protection of forests throughout their ranges. Frugivores and short-distance migrants seemed to be more heavily impacted during the non-breeding period than during the pre-breeding, breeding or post-breeding periods and would thus benefit from temporally- targeted habitat protection. Braun et al. (2023) modeled changes in distribution for twelve migratory marine top predator species in two rapidly warming areas: the Northwest Atlantic Ocean and Gulf of Mexico. Their data-assimilating ocean model, which used data from both in-situ and remote sensing platforms, predicted widespread losses of suitable habitat for most species, concurrent with substantial northward displacement of core habitats (>500 km) and constituting losses in suitable habitat of up to >70% for some commercially and ecologically important species. These changes are already underway for several species. Barenblitt et al. (2023) documented the extent of the Nypa palm (*Nypa fruticans*) in Nigeria using European Space Agency Sentinel-1 synthetic aperture radar data and a random forest classifier, along with GEDI lidar products. The spread of this introduced species threatens the largest continuous mangrove system in the world within the Niger Delta. Indeed, the authors found that approximately 28,000 hectares of mangroves had been converted to Nypa palm by 2020, covering a larger extent than the endemic mangrove vegetation in the study area, and showing rapid expansion since 2015. In addition, Nypa palm has a higher understory density than the endemic mangroves, which will likely have extensive effects on the use of the invasive Nypa forests by native wildlife.

Floating debris, whether it is naturally generated like Sargassum, or of human provenance like marine plastics, can play a role in the dispersal of organisms, as well as in the creation of miniature ecosystems. Chong et al. (2023), as part of a community science initiative, examined the North Pacific "Garbage Patch" to better understand whether marine debris aggregates provided habitats for marine surface-dwelling organisms (obligate neuston). They found a positive relationship between the abundance of some neuston taxa and plastic, suggesting that marine debris could be serving an ecosystem function analogous to *Sargassum* in the Sargasso Sea. Haram et al. (2023) analyzed plastic rafts in the eastern North Pacific Subtropical Gyre and found that the richness of coastal invertebrate taxa exceeded the richness of pelagic taxa threefold. There was evidence of reproduction in both pelagic and coastal taxa on the plastic rafts collected. The authors noted that floating marine plastic debris supports sustaining ecosystems in the open ocean in which coastal species persist as a substantial component of a "neopelagic community." Both authors utilized QuikSCAT and ASCAT wind and other satellite products for their surface current models. Lastly, Hu et al. (2023) refined their *Sargassum* near real-time monitoring in nearshore areas (up to 30 km from shoreline) by merging multi-sensor observations. Pelagic *Sargassum* in the Atlantic Ocean is an important habitat for marine life, but its significant increase in biomass since 2011 keeps causing many problems for nations and ecosystems that are impacted by massive beaching of this macroalgae.

Wildfires

Wildfire is a growing problem in the United States. In 2020 alone, there were over 58,000 wildfires resulting in over 10M acres burned. Five-year average fire suppression costs are about

$2.35B, not including costs associated with property damage and impacts to human health, which are estimated to be far greater. The wildfire problem and associated costs are expected to grow under projected climate change; therefore, it is critical to understand and manage wildfires across their entire lifecycle which includes the pre-fire, active fire, and post- fire environments. Improved understanding of these environments can lead to enhanced wildfire management, including pre-fire risk reduction, efficient active fire suppression, and effective post-fire hazard mitigation, ultimately reducing negative ecosystem impacts and damage to property and people. In FY23, NASA ESD began a new project called FireSense, which is focused on delivering NASA's unique Earth science and technological capabilities to operational agencies, striving towards measurable improvement in US wildland fire management. Through initial stakeholder engagement activities, the FireSense project will begin by perusing four uses-cases focused on characterization and measurement of (i) pre-fire fuels conditions, (ii) active fire dynamics, (iii) post fire impacts and threats, and (iv) air quality impacts and forecasting, each co-developed with identified stakeholders. The FireSense project will include an airborne science component (annual campaigns) where improved capabilities and technologies will be developed and

evaluated, and ultimately demonstrated to agency stakeholders in a large capstone airborne campaign in year 5 of the project (2027-2028). The first airborne campaign will take place in October of 2023, in concert with a large prescribed fire in the Fish Lake National Forest, working closely with fire managers from the US Forest Service and the associated US Forest Service research project Fire and Smoke Model Evaluation Experiment (FASMEE). In addition to acquiring data over the Fish National Forest prescribed fire, additional targets of opportunity include other prescribed fires and ongoing wildfires. During the field campaign, a series of sensors will be flow to characterize the pre-fire (AVIRIS-3, UAVSAR, SLAP), active fire (SWIS, CMIS, MASTER, AVIRIS-3), and post-fire (AVIRIS-3, UAVSAR) environments.

Airborne and surface-based activities

Airborne and surface based (field) activities have continued steadily after the hiatus caused by the COVID-19 pandemic. Some of the highlights of field work for 2022 are below.

ABoVE

Field work for ABoVE Phase 3 became active in 2023 post-COVID. The new AVIRIS-3 airborne sensor has been deployed in the ABoVE domain for its first operational data collection. AVIRIS-3 provides increased signal to noise ratios (SNR) and finer spatial resolution than the AVIRIS-NG sensor which had been used in the 2017-2019 and 2022 campaigns. Alaskan operations began in mid-July although smoke from the widespread Canadian fires interfered with data collections in Interior Alaska and the Yukon Territory. Nonetheless, the team succeeded in acquiring high priority surveys across the domain through mid-August 2023. Field work included projects examining the spectral characteristics of boreal and tundra vegetation, examining dynamics of repeat fires in the Northwest Territories of Canada, long-term measurements of soil respiration across the ABoVE domain, identifying disturbances and societal vulnerabilities of oil and gas exploration in permafrost areas, and the hydrological and biogeochemical impacts of expanding beaver ponds in tundra areas.

LVIS/GEDI Cal-Val for AfriSAR-2

The LVIS airborne lidar returned to Gabon in May 2023 for the AfriSAR-2 campaign in collaboration with the European Space Agency. LVIS collected data over areas sampled in 2016 to examine change detection as part of the GEDI cal-val. LVIS also collected data over GEDI lines in Gabon, Cameroun and Congo-Brazza. Data was collected at the same time the ESA FSAR sensor was also collecting data over high priority field sites in Gabon. In September and October 2023, NASA intends to execute an airborne campaign over these and other field sites in central Africa with the L-Band and P-Band systems of UAVSAR as part of AfriSAR-2.

NASA's Carbon Monitoring System

Underlying policy efforts to address global climate change is the scientific need to develop the methods to accurately measure and model carbon stocks and fluxes across the wide range of spatial and temporal scales in the Earth system. Initiated in 2010, the NASA Carbon Monitoring System is one of the most ambitious relevant science initiatives to date, exploiting the satellite remote sensing resources, computational capabilities, scientific knowledge, airborne science capabilities, and end-to-end system expertise that are major strengths of the NASA Earth Science program. In the process, CMS scientists actively engage with stakeholders at the federal, state, and local level, as well as with international partners. Recent (FY23) major successes include development of the first remote-sensing based forest carbon monitoring system in official state use (MDE 2022, MDE 2023), quantification of trends in industrial methane emissions (Yadav et al 2023), multi-scale observations of blue carbon fluxes (Poulter et al. 2023), and characterization of global CO2 flux anomalies (Feldman et al 2023). CMS also contributes to the new National GHG

Center. To date, the initiative has engaged with >200 stakeholders and produced >650 publications and >130 data products cited >50,000 times.

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

The Earth's cryosphere covers continent-sized areas in the most inaccessible and inhospitable regions of the globe. NASA's capabilities in satellite and aircraft remote-sensing are critical tools for understanding the changes occurring there. NASA's Cryospheric Sciences Program supports studies based on satellite and aircraft remote sensing observations to understand the factors controlling changes in the ice and its interaction with the ocean, atmosphere, solid earth, and solar radiation.

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. Increases in ice loss from the glaciers of Antarctica, Greenland, and the rest of the Arctic are contributing to sea level rise, while similarly dramatic changes are occurring in the sea ice cover of the Arctic and Southern Oceans. Characterizing these changes and understanding the processes controlling them is required to improve our understanding of the Earth system and forecast the impacts of continued change.

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.

Sea ice pressure ridges, which form as a result of convergence and deformation between ice floes, restrict the movement of air across sea ice and pose an impediment to transport across or through the ice by humans, animals or marine vessels. Using ICESat-2 laser altimetry data, *Duncan & Farrell (2022)* calculated surface roughness and measured the sail height and frequency of pressure ridges across the Arctic. Their methods identified sea ice ridges and reproduced sea ice deformation statistics at an along-track resolution previously only attainable from airborne platforms. They found that while year-to-year variability in pressure ridge morphology is low, regional variations are significant, and found distinct deformation characteristics depending on the parent ice type which is consistent with previous studies. The results demonstrate that high-resolution satellite altimeter observations can be used to derive detailed measurements of sea ice topography that will ultimately support process studies and advances in sea ice modeling.

Land Ice in the Climate System

The largest uncertainty in future projections of sea level change comes from the response of the Antarctic Ice Sheet to the warming oceans and atmosphere. Numerous studies have shown that the ice sheet is currently out of long-term equilibrium, and is losing mass at an accelerated rate and increasing sea level rise. The longest observational record available to study the mass balance of the Earth's ice sheets comes from satellite altimeters. However, this record consists of multiple satellite missions with different life spans and inconsistent measurement types (radar and laser) of varying quality. To fully utilize these data, measurements from different missions must be cross-calibrated and integrated into a consistent record of change. *Nilsson et al. (2022)* presented an intuitive approach for generating a record that implies improved topography removal, cross-calibration, and normalization of seasonal amplitudes from different missions. They detailed the geophysical corrections applied and the processes needed to derive elevation change estimates. They processed the full archive record of satellite altimetry data, providing a seamless record of elevation change for the Antarctic Ice Sheet that spans the period 1985 to 2020, and the data were produced and distributed as part of the NASA MEaSUREs ITS_LIVE project.

Antarctica’s floating ice shelves modulate discharge of grounded ice into the ocean by providing backstress. Ice shelf thinning and grounding line retreat have reduced this backstress, driving rapid drawdown of key unstable areas of the Antarctic Ice Sheet. *Paolo et al. (2023)* analyzed 26 years (1992—2017) of changes in satellite-derived Antarctic ice shelf thickness, flow and basal melt rates to construct a time-dependent dataset and investigate temporal variability. They found an overall pattern of thinning around Antarctica, with a thinning slowdown starting around 2008 widespread across the Amundsen, Bellingshausen and Wilkes sectors. This slowdown was attributed partly to modulation in external ocean forcing, likely altered in West Antarctica by negative feedbacks between ice shelf thinning rates and grounded ice flow, and sub-ice-shelf cavity geometry and basal melting. However, they also note that available observations span only

26 years, and the reduction in thinning reported may represent a temporary adjustment period on decadal timescales. Their satellite-derived ice shelf thickness and basal melt dataset used a novel data fusion approach, state-of-the-art satellite-derived velocities, and a new surface mass balance modeling.

The East Antarctic Ice Sheet contains the vast majority of Earth's glacier ice, but is often viewed as less vulnerable to global warming than the West Antarctic or Greenland ice sheets. However, some regions of the East Antarctic Ice Sheet have lost mass over recent decades, prompting the need to re-evaluate its sensitivity to climate change. *Stokes et al. (2022)* review the response of the East Antarctic Ice Sheet to past warm periods, synthesize current observations of change and evaluate future projections. Some marine-based catchments that underwent notable mass loss during past warm periods are losing mass at present but most projections indicate increased accumulation across the East Antarctic Ice Sheet over the twenty-first century, keeping the ice sheet broadly in balance. The authors document an urgent need to understand the sensitivity of basal melting to ocean temperatures and for more detailed observations of continental-shelf bathymetry, bedrock topography proximal to, and up-ice from, current grounding lines and improved observations of sub-shelf cavities and oceanic processes.

Rapid retreat of Antarctic ice shelves in a warmer climate remains challenging to predict, contributing to uncertainties in projections of sea level rise. Despite a general consensus that regional climate warming is associated with ice shelf collapse, knowledge of the precise details leading to and following collapse is limited. *Wang et al. (2023)* presented a detailed analysis of multidecadal evolution of the northern Larsen Ice Shelf from the mid-1960s to the present based on a comprehensive set of satellite observations, modeling experiments, and climate reanalysis data. Their analyses revealed a complicated process of ice shelf instability development that is intricately linked to front geometry, effective buttressing sources, shear margins, ice mechanical conditions, and external forcing associated with atmospheric and oceanic temperature anomalies. Satellite data suggest that a major transition in calving style, from a pattern of infrequent large-tabular-iceberg calving to frequent small-iceberg calving, is a precursor of ice shelf disintegration. This calving style transition coincides with a sharp shift in the pattern of flow acceleration, from localized down-glacier acceleration to ice-shelf-wide faster acceleration. These observable changes via remote sensing systems may serve as precursory indicators for predicting potential ice shelf collapses in the future.

Oceans in the Climate System

The oceans play a fundamental role in the Earth system. The continuous exchange of heat, water, moisture, and gasses between the ocean and the atmosphere influence climate and weather patterns by releasing the heat that fuels the overlying atmospheric circulation, releasing aerosols that impact cloud cover, absorbing and storing atmospheric CO_2 for millennia, and by releasing moisture that determines the fate of the global hydrological cycle.

NASA's Physical Oceanography Program (PO) supports a wide range of studies that quantify the ocean's role in the Earth climate system by utilizing remote and in situ observations, numerical models, and data assimilating systems. The program supports research that characterizes the ocean's intrinsic variability, its dynamics and thermodynamics, and its interactions within the complex system of ocean-atmosphere-land-solid Earth. Below are the most notable discoveries in 2022-2023 that advanced our understanding of the ocean's role in the climate system.

Ocean dynamics regulate Earth's heat

The year 2023 has seen the highest ocean temperatures recorded by satellites over the past 40 years, with global average surface temperature (land and ocean) this summer surpassing a 1.5°C threshold for the first time during summer in the Northern Hemisphere. Across all ocean basins of the Atlantic, Pacific, and Indian Oceans, anomalies in sea surface temperatures were reaching 5-10°C as reported by multiple of NASA's and other agencies images (e.g., NASA image of ocean temperatures off South Florida reaching over ~37°C /100°F), initiating a series of long-lasting extreme events like ocean heat water across the globe that will be described in the following section below.

Beyond the surface, ocean warming continued unabated all the way towards the abyss, as tracked by the NASA ECCO ocean/ice state estimate, which shows an accelerated accumulation of heat in the vertically-integrated, surface-to-bottom, pole-to-pole estimates of the ocean heat content, complementing NOAA's upper-ocean estimates of heat content. In particular, the rate of the energy uptake of the ocean, and thus Earth's climate system, has roughly doubled over the past 15 years (e.g., *Johnson et al. 2023*). This year, ECCO's information on ocean warming was included, for the first time, in the joint NASA/NOAA joint press release on global temperatures, providing additional insights of planetary warming and the ocean's role in Earth energy budget.

To coordinate Agency-wide efforts towards understanding and predicting ocean's storage and release of the excessive heat accumulated in the Earth system, the PO program established a new NASA Working Group on Ocean Heat and Earth Energy Imbalances (OHC/EEI). The WG used satellite (Jason-series altimetry, GRACE, GRACE-FO) and in situ observations to report that over the past decades, the Earth system has been accumulating heat at a rate of 0.48+/-0.1 W/m^2 (*von Schuckmann et al. 2023*), of which about 90% goes into the ocean, 2% in the atmosphere, and the remaining 8% on land, including ice. . An even higher heating rate is recorded over the past 15 years, amounting to 0.76±0.2 W/m^2 .The OHC/EEI WG group further notes that the estimates of the long-term energy uptake can be obscured by a large seasonable cycle in the energy storage. For the ocean, the long-term rate of energy uptake by the global ocean is about 10 ZJ/year, whereas annually the ocean absorbs and releases 63.5 ZJ within a year (e.g., *Johnson et al. 2023*). This seasonal variation in energy in and out of the ocean follows an annual harmonic, with the maximum heat storage in April followed by a rapid discharge of heat over the following 5 months (*Johnson et al. 2023*).

Storage, release, and redistribution of heat in the ocean is mainly accomplished by ocean mixing of heat anomalies throughout the water column. Therefore, prediction of an overall trajectory of a warming Earth, understanding of ocean mixing, its effective rates, and depths at which the most vigorous mixing occurs (referred to as a mixed layer) is a priority for the NASA PO program. A new study by *Yu et al. (2023)* characterizes sensitivity of the ocean mixed layer depth to the intrinsic ocean dynamics that takes place at and below the ocean surface. Their results show a strong correlation between the annual changes in the depth of the thermocline, wave heights, and sea surface slope. Their conclusions about the seasonal changes in the thermocline depth and heat storage will benefit from an enhanced spatial resolution of SWOT sea surface height data, which are coming soon following the launch in December and a successful maneuver into its operational orbit in July 2023.

Other notable studies connecting major ocean transport and circulation, including the Atlantic Meridional Overturning Circulation, to the climate sensitivity included works by *Romanou et al. (2023)* and *Orbe et al. (2023).*

Ocean salinity constraints Earth energy and water cycles

NASA salinity remote sensing continues to improve our knowledge of Earth's energy and water cycle. Members of the NASA Ocean Salinity Science Team, including recent study by *Liu et al. (2023)* provide additional evidence that ocean salinity emerges as an important constraint in Earth's heat and freshwater budgets. As a state variable controlling ocean density and thus ocean stratification, ocean salinity can enhance or inhibit ocean heat uptake, with direct implications for climate sensitivity. In a recent study, *Liu et al. (2023)* demonstrate how human-induced changes in ocean salinity, including amplification of the spatial contrasts in sea surface salinity and salinification, result in a weaker upper-ocean stratification which in turn enhances the rates of the ocean heat uptake. The results of this study demonstrate the critical role of ocean salinity controlling the efficiency of ocean heat uptake, which in turn determines future rates of warming on land. Continued salinity measurements from NASA's SMAP and former Aquarius missions, combined with in situ salinity data, are proving a critical tool to predict ocean's heat and energy budget and Earth's transient climate response.

In addition to Earth's energy budget, salinity information has proven useful in prediction of different components of the Earth's water cycle, including precipitation and flooding on land. Given the sensitivity of ocean salinity of freshwater input that tends to dilute ocean surface and decrease its salinity, exploring potential linkages and practical relationship between ocean salinity and the global water cycle is one of the priorities for the PO program and NASA Ocean Salinity Science Team. A recent study by *Li et al. (2022)* uses salinity information to predict precipitation in the U.S. Midwest region – an agriculturally important region and a world leader of crop production. *Li et al (2022)* use machine learning approaches and information of surface salinity from NASA satellites to predict heavy rainfall in the U.S. Midwest, aiding local farmers to determine the types of crop to plant and properly prepare for watering needs. The results of *Li et al (2022)* show that salinity information yields a skillful prediction of Midwest heavy rain, compared to prediction based on sea surface temperature alone, with salinity-based predictors improving the accuracy of heavy rainfall prediction by 92%, albeit more work needs to be done to improve overall accuracy of the predictions Results of this study is a continued demonstration of the utility of NASA salinity remote sensing and the key role of ocean salinity in Earth's water cycle, connecting its different components like evaporation, precipitation, atmospheric circulation and moisture transport, and soil moisture feedback.

Air-sea coupling and fluxes regulate weather and global climate

The National Academies' Decadal Survey for Earth Science and Applications (2017) identified simultaneous measurements of ocean surface wind and currents as a "Targeted Observable" to be addressed through the competitive Earth System Explorer program (see their Table 3.7). Exploring science benefits of this novel, simultaneous retrieval of ocean winds and currents is one of the priorities of the NASA Ocean Vector Winds Science Team. To address this priority, a new study by its members *May and Bourassa (2023)* conducted a modeling study to explore dynamic interaction between the winds and currents in the context of air-sea coupled processes, like storms and hurricanes. They found that accounting for active interaction between winds and currents inhibits strong upward vertical motion in the atmospheric boundary layer, and thus weakens storms as a direct response of the wind/stress/current interaction. Their results have implications for improving predictive capabilities of weather forecasting systems, which will benefit from direct and global observation of simultaneous wind and current measurements.

As a practical application of a wind/current mission, a new study by *Wang et al. (2023)* explore the utility of collocated measurements for the U.S. Energy sector, focusing on electrical power generation. The study argues that the wind power density along the U.S. coastal region is correlated with various climate indices, and describes how new measurements, including wind speed and direction, can provide a useful approach for predicting available wind power for the U.S. coastal users.

Another priority of the PO program pursued by the NASA Ocean Vector Wind and SWOT Teams is understanding and predicting air-sea coupling and exchange on a wider range of spatial scales, moving towards smaller, sub-mesoscale processes (enter SWOT!). A new study by *Seo et al. (2023)* provides a comprehensive review of air–sea interaction as a function of scale, and outlines recommendations on theoretical, observational, and modeling strategies for future research. New analysis by *Seo et al. (2023)* can have important implications for future satellite missions that aim to resolve submesoscale air-sea fluxes in latent and sensible heat, momentum, and CO_2, which are important drivers of Earth's fundamental energy and biogeochemical cycles.

Another PO program focus is to monitor known modes of climate variability in air-sea interaction, which is pursued within the NASA Ocean Surface Topography Science Team. A strong air-sea coupling is particularly prominent in the tropical and equatorial ocean regions, where the ocean exerts a strong feedback on atmospheric motions, producing coupled ocean-atmospheric oscillations, such as El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Madden-Julian Oscillation (MJO), that are often linked to weather anomalies on land. This year, NASA released a new public tool to monitor the formation of the ocean waves, referred to as Kelvin waves, that traverse the equator and bring warm water from the western side of the Pacific to its eastern side, towards South America. The powerful Kelvin waves are seen as higher seas in Sentinel-6 MF data, and are often used as a precursor of El Niño conditions, which has been discussed as one of the contributing factors for the extreme ocean summer temperatures as detailed below.

Ocean extremes and coastal hazards

Multiple observational and modeling evidence suggest that, in addition to low-frequency, secular trends, there are also measurable changes in the current higher-frequency and extreme ocean events, including ocean heat waves, high tides, storms, floods, etc. Understanding and predicting ocean extreme events is thus an important focus for the PO program.

The year 2023 provided abundant data to observe marine heat waves across the globe. By definition, a heat wave is an extreme event, a spike in regional temperatures that ranks among the top 10% warmest over the past 30 years. This year 40%-50% of the world's oceans were experiencing marine heat waves – the most amount of such extremes over the past 30 years of satellite monitoring. Extreme ocean temperatures recorded in the North Atlantic, Mediterranean Sea, Eastern Pacific, Indian Ocean and others, were linked to extreme weather events on land, including fires in Greece and Canada.

While the main cause of the occurrence of the marine heat wave is the underlying planetary warming, a developing El Niño has been identified as another potential contributor to this year's marine heat waves. Associated with the weakening of the trade winds over Pacific and Atlantic oceans, El Niño conditions are thus decreasing evaporation over the ocean, allowing ocean temperatures to rise more rapidly. While temporarily masked by cooling La Niña conditions that have been prevailing over the past few years, warming becomes more evident during neutral or El Niño conditions, including this summer.

A new mechanism for La Niña formation was offered by *Fasullo et al. (2023)*, who offered a new connection between the smoke from wildfires and climate, arguing that extreme wildfires in Australia triggered a stronger than usual La Niña 2019-2020. *Fasullo et al. (2023)* suggest that the Australian wildfires caused an increase in organic matter emission into the atmosphere, leading to more cloud cover and less sunlight reaching the Earth's surface, with subsequent decrease in humidity and temperatures, all triggering a "surprising" La Niña that lasted three years up until now. The mechanism is similar to the impact of the volcanic ash, which can temporarily mask global warming and even cause a dip in the global mean sea level (e.g., the eruption of the Mt. Pinatubo in 1991), and the authors might have started a new debate about the robustness of this connection.

Recent studies have also shown that marine heat waves are no longer a surface feature, but can extend below the surface or all the way to the ocean bottom, particularly on shallow shelves. For low-lying coastal areas, a compounding effect of surface and subsurface heating is the expansion of the ocean water column or sea level rise. A new study by *Han et al. (2022)* investigates such an effect in low-lying Indonesian coastal regions. They conclude that in a warming climate, the occurrence of marine heat waves has increased, and with combined increase in global mean sea level, have larger ecological and socio-economic impacts for the vulnerable coastal communities and ecosystems. In addition, the compound effects of ocean extremes become further exacerbated during El Niño years, as we are seeing today.

<u>Integrated Earth System and Modeling</u>

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.

Numerous studies utilizing these models and other MAP supported modeling efforts have improved the characterization of various components of the Earth system and the naturally occurring and human-induced forcing that act upon it. Several major achievements over the past year are highlighted in the following:

Climate modeling advances

Physical representations and configurations in GISS Model E have evolved extensively from version GISS-E2.1 to version GISS-E3. *Li et al. (2023)* presents a performance assessment of GISS-E3 vs. GISS-E2.1 in simulating the present-day Pacific climate using the CMIP6 protocol. Compared to GISS-E2.1, GISS-E3 features greatly reduced discrepancies w.r.t. satellite observations in many key variables, including ice water content and path, radiative fluxes, surface wind stress, sea surface temperature (SST), precipitation, and column water vapor over south Pacific oceans. Particularly, biases in the cloud only ice water path (CIWP) are reduced substantially from ∼400 $g\ kg^{-1}$ in GISS-E2.1 to 10–20 $g\ kg^{-1}$ in GISS-E3. The combination of more accurate CIWP and the inclusion of snow in GISS-E3 improves the estimate of Earth's radiation budget. Over south Pacific, especially the trade wind regions, the improved surface wind stress associated with inclusion of snow-radiative effects in GISS-E3 improves the estimates of radiative fluxes, SST, precipitation, and column water vapor. Longstanding warm SST bias over trade-wind regions and cold SST biases over north Pacific Ocean are significantly reduced.

A myriad of biogeophysical and biogeochemical feedbacks exist between the climate system and land ecosystems. A demographic vegetation model, BiomeE, has been developed in the NASA GISS ModelE Earth system model to improve the modeling of vegetation dynamics and ecosystem biogeochemical cycles (*Weng et al., 2022*). This model includes the processes of plant growth, mortality, reproduction, vegetation structural dynamics, and soil carbon and nitrogen storage and transformations. Overall, the BiomeE model simulates, with fidelity comparable to other models, the dynamics of vegetation and soil biogeochemistry, including leaf area index, vegetation structure (e.g., height, tree density, size distribution, and crown organization), and ecosystem carbon and nitrogen storage and fluxes.

Chemistry/climate modeling advances

Stratospheric composition is important to the ozone layer recovery and for the planet's radiative budget. A new reanalysis, namely the MERRA-2 Stratospheric Composition Reanalysis of Aura Microwave Limb Sounder (M2-SCREAM), has been produced at NASA's Global Modeling and Assimilation Office (*Wargen et al., 2023*). The stratosphere-focused M2-SCREAM product uses high quality data from the Microwave Limb Sounder (MLS) instrument (2004-present) combined with meteorological information from the MERRA-2 reanalysis to generate assimilated global three-dimensional distributions of 3-hourly ozone, water vapor, hydrogen chloride, nitric acid, and nitrous oxide, all of which are of primary importance to stratospheric chemistry and transport studies. Comparisons against independent observations show that the reanalysis realistically captures the spatial and temporal variability of all the assimilated constituents. This demonstrates the utility of M2-SCREAM for scientific studies of chemical and transport variability on time scales ranging from hours to decades.

The GEOS Composition Forecast (GEOS-CF) provides recent estimates and 5-day forecasts of atmospheric composition to the public in near-real time. GEOS-CF product has been used in many applications and composition analysis. *Kerr et al. (2022)* presents an example of using GEOS-CF products to analyze contributions of diesel-powered vehicles emissions to nitrogen dioxide (NO_2) pollution. The COVID-19 pandemic and ensuing changes in emissions provide a natural experiment to test whether NO_2 reductions have been starker in regions of Europe with larger diesel passenger vehicle shares. *Kerr et al. (2022)* used a semi-empirical approach that combines in-situ NO_2 observations in urban areas and GEOS-CF product within a machine learning algorithm to estimate business-as-usual NO_2 during the first wave of the COVID-19 pandemic in 2020. Comparing the observed NO_2 concentrations against business-as-usual estimates indicates that diesel passenger vehicle share was a major factor in determining the magnitude of NO_2 reductions. European cities with the five largest shares of diesel passenger vehicles experienced NO_2 reductions ~2.5 times larger than cities with the five smallest diesel shares. Results from this study have implications for potential NO2 reduction from future phase out of passenger vehicles from cities.

Land and land/atmosphere coupling modeling advances

For all their complexity, and for all the work that underlies their development, the land surface model (LSM) components of Earth system models may be suboptimal in fundamental yet unstudied ways. Past work has shown that a LSM's implicit (not explicitly coded) relationships between soil moisture and both evapotranspiration (ET) and runoff largely determine the LSM's hydrological behavior. *Koster et al. (2022)* estimated how the joint control of soil moisture over ET and runoff processes in nature differs from that built implicitly into a state-of-the-art land model. The study explores relationships between soil moisture and runoff by calibrating them within a simple water balance model (WBM). Results suggest that observation-calibrated ET and runoff efficiency functions successfully represent, to some degree, soil moisture controls over hydrological variability in nature and can serve as potentially useful targets for further LSM development[YH(61] . Another study, *Reichle et al. (2023)*, introduces a land analysis into the GEOS Hybrid-4DEnVar system to additionally assimilate L-band (1.4 GHz) brightness temperature observations over land from the NASA Soil Moisture Active Passive (SMAP) satellite. Retrospective assimilation experiments for boreal summer 2017 were conducted with the system at 50 km horizontal resolution. The SMAP assimilation is shown to mitigate errors in screen-level (2 m) specific humidity (q2m) and temperature (T2m). With the SMAP assimilation, forecasts of q2m and T2m have significantly improved anomaly correlation and RMSE (99% confidence) at lead times out to 5 days, with medium-range lead times extended by ~3 hr for q2m and ~2 hr for T2m. Temperature and humidity forecasts at the 925 and 850 hPa levels are also improved.

Seasonal variability of the global hydrologic cycle directly impacts hazard assessment and mitigation, agricultural decisions, and water resources management. This is particularly true across the High Mountain Asia (HMA) region, where availability of water resources can change depending on local seasonality of the hydrologic cycle. The GEOS subseasonal to seasonal (S2S) prediction system has developed the capability to forecast the atmospheric states and surface conditions, including variables relevant for hydrometeorology, at S2S lead times of weeks to months. *Massoud et al. (2023)* presented a benchmark of the GEOS-S2S (Version 2) forecasting skills for hydrometeorological variables at 1–3-month lead times in the HMA region, including a portion of the Indian subcontinent, during the retrospective forecast period of 1981–2016. These variables including the 2m air temperature, total precipitation, fractional snow cover, snow water equivalent, surface soil moisture, and terrestrial water storage, were benchmarked against the Modern-Era Retrospective analysis for Research and Applications, Version 2

(MERRA-2) and independent reanalysis data, satellite observations, and data fusion products. The results suggest that, generally, hydrometeorological forecast skill is dependent on the forecast lead time, the memory of the variable within the physical system, and the validation dataset used.

Ocean/atmosphere coupled modeling advances

The ocean has absorbed roughly 40% of fossil fuel carbon dioxide (CO_2) emissions since the beginning of the industrial era. This so-called "ocean carbon sink," which primarily sequesters emissions in the form of dissolved inorganic carbon (DIC), plays a key role in regulating climate and mitigating global warming. The inventory and variability of oceanic DIC is driven by the interplay of physical, chemical, and biological processes. There is substantial compensation between budget terms, resulting in distinct upper-ocean carbon regimes. *Carroll et al. (2022)* used the global-ocean biogeochemistry modeling system ECCO-Darwin to map how ocean circulation, air-sea CO_2 exchange, and marine ecosystems have modulated the natural and anthropogenic DIC budget in surface oceans for 1995–2018. They found that in the upper ocean, circulation provides the largest supply of DIC while biological processes drive the largest loss. Interannual variability is dominated by vertical advection in equatorial regions, with the 1997–1998 El Niño-Southern Oscillation (ENSO) causing the largest year-to-year change in upper-ocean DIC. This work provides a novel, data-constrained framework for an improved mechanistic understanding of natural and anthropogenic perturbations to the ocean carbon sink. Quantifying the spatiotemporal variability of these drivers is also crucial for predicting its future trajectory.

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, tsunamis, 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]. These same seven challenges were then used as a basis to determine ESI-related science priorities in *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space* (National Academies of Sciences, Engineering and Medicine, 2018, https://nap.nationalacademies.org/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth). The ESI chapter summarizes highlighted accomplishments of the past year that respond to addressing these seven *CORE* challenges and associated *Decadal Survey* goals. 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. In 2023 ESI had an increase in support of Earth System Observatory (ESO) missions, with publications supporting the Surface Biology and Geology (SBG), Mass Change (MC), and the NASA-ISRO SAR (NISAR) missions. There was also an increase in multi-parametric data being used to resolve issues ranging from characterizing hazard monitoring data to reducing error sources. It is believed this is the result of increased accessibility of data and algorithms and communication within the ESI community.

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

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.

Argus et al., (2022) combined GPS and GRACE to infer changes in groundwater storage in the Central Valley as well as the Sacramento-San Joaquin-Tulare River basin, its source watershed. They found that from 2006 to 2021 the Central Valley has been losing an average 2.2 ± 0.7 km^3/yr with 2/3 of the groundwater loss being concentrated in the southern third of the valley. This study is impactful in that it provides a quantitative value for changes in total water storage in this area. Additionally, they have inferred changes in bedrock groundwater by removing signals from snow water and soil moisture by creating a composite model using GPS and GRAGE. White et al, 2022 produced a broad study on how GNSS/GPS data can be used in hydrogeodesy to encourage the community in using it as a tool in investigating and quantifying water resources. They describe how GNSS time series respond to changing input of rain, snow, and groundwater loss when estimating terrestrial water storage and offer ideas about pressing questions in hydrology that GNSS may help solve.

Anthropogenic Deformation

Anthropogenic processes can also play a role in surface deformation. By understanding what these processes are and how they impact surface deformation researchers can have more accurate measurements of natural deformation causes and have a better understanding of how humans impact the surrounding environment.

Zheng et al., (2023) studied how deformation was induced by wastewater injection from 2014 to 2020 in west Texas using Sentinel 1A/B C-band time series data and applying a Bayesian Monte Carlo inversion model to invert for the properties of the surrounding rocks. They found that the volumes needed to correlate with the results in the dominant injection well were ~2.6 times larger than the reported volumes. Additionally, their analysis provided a new technique to estimate local hydrogeologic properties which can serve as a reference for adjacent oil fields. Qu et al., (2023) mapped and characterized land deformation along the Gulf Coast from 2007 to 2011 using ALOS-1 L-band InSAR data by constructing a deformation map over 500,000km^2. They identified 30 subsidence patterns and 14 uplift features that have been attributed to regional geologic conditions and human activities that have influenced the natural surroundings such as wastewater injection, oil field pumping depressurizing petroleum reservoirs, aquifer compaction from ground water extraction, sulfur/salt mining. dewatering, oxidation, and construction work. Most of the identified ground instabilities are newly discovered as a result of this study and will help the scientific community and relevant agencies better understand land deformation rates and extents, identify the processes responsible for the coastal deformation, and provide a critical dataset for hazard prediction and mitigation.

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 of the drivers for the behavior of earthquake events.

In a combination of studying fault dynamics and anthropogenic deformation Horne et al. (2022) studied the shallow fault system in the Delaware Basin of Texas and New Mexico using InSAR in combination with 3D seismic reflection data to characterize a series of elongate, narrow, and extensional graben faults. This area is experiencing elevated levels of seismicity that is believed to be associated with these faults. InSAR observations revealed that this faulting system may be slipping asiesmically from the nearby oilfield operations of hydraulic fracturing and wastewater disposal.

Li et al. (2023) research spatiotemporal variations of surface deformation, shallow creep rate, and slip partitioning between the San Andreas and southern Calaveras Fault using Sentinel-1 InSAR collected from May 2015 to October 2020. They found that both faults are creeping asiesmically at the surface with different rates, which is atypical for faults so close to each other. They observed a slowdown in fault creep during 2016–2018 on the SAF, confirmed by analysis of clusters of small earthquakes and repeating earthquakes that have nearly identical seismic waveforms. This leads to the conclusion that the SAF is extremely sensitive to small loading perturbations whereas the CF is not. The study demonstrated how remote sensing techniques can be used to measure subtle large-scale ground deformation with good spatial and temporal accuracy, which is important for monitoring fault slip behaviors and assessing seismic hazards. Xu et al., (2023) sought to better understand the rupture process of the 2021 Mw 7.4 Maduo Earthquake using slip model and 3D ground displacement from Sentinel-1A/B InSAR data. They found a left-lateral strike-slip rupture with a branching split to the east end. This split in the rupture was found to be caused by regional stress orientation, rupture speed, and fault branching angle. This finding is important in helping researchers understand the elements that lead to the propagation of faults.

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. Wang et al. (2023) performed an analysis of the 8 July 2021 Antelope Valley earthquake using a finite -source model derived from InSAR, GNSS, and seismic data. They found that aftershocks continued to occur for one year after the mainshock and within 2-3 km around the up-dip portion of the main rupture plane with little to no activity occurring below 10km. This suggests a brittle to ductile transition in this area, however there were also shallow afterslips observed at a shallow depth beneath Antelope Valley fault that were east of the mainshock rupture. The researchers found that these Antelope Valley afterslips are in an area of substantial Coulomb stress increase, which coupled with a lack of post seismic deformation seen by InSAR, suggests a potential for shallow seismic activity in the area. Parameswaran et al., (2023) used GNSS-derived velocity waveforms interchangeably with seismic data for characterization of peak ground velocities (PGVs) that typically rely on strong seismic data during the 2021 Chignik earthquake. They found that GNSS and seismic records were almost identical when observed at frequencies < 0.25 Hz and that GNSS data could be used to generate rapid estimates of PGV-derived moment magnitudes for the earthquake. The researchers suggest this study confirms that GNSS is a powerful alternative or addition to seismic data and vice versa.

The July 5, 2019, Ridgecrest earthquake was the first earthquake centered in southern California to rupture the ground surface since the 1999 Hector Mine Earthquake. The seismic sequence was well monitored and was the focus of many researchers in the past year. Aati et al., (2022) developed an end-to-end procedure to produce high quality 2D and 3D surface displacement measurements from optical Digital Elevation Models (DEMs). This technique was used to generate a 3D cosiesmic displacement map over Ridgecrest that generates high quality measurements of coseismic ground displacement with GSD of 2.4 m which the authors demonstrate outperforms the more standard approach of 2D modeling. This same technique could be expanded to study other processes causing displacements of the earth surface, such as slow-moving landslides, sand dune migration, volcanic deformation, and ice flows. It has the potential to have a large impact on the surface displacement community. Barba-Sevilla et al., (2022) used 3D finite element modeling to develop a high-resolution finite fault slip inversion for Ridgecrest. This model included complex rheology and fused synthetic aperture radar-Global Navigation Satellite System data to produce a more complete fault slip model at all depths. This resulted in a more detailed model for the entire seismogenic zone with reasonable computational cost and providing new insights into the governing rheologic and structural processes.

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.

Corradino et al., (2023) applied a deep learning, convolutional neural network (CNN), approach to ASTER Thermal Infrared (TIR) data to automatically detect subtle thermal features that typically require manual analysis at five different volcanoes with varying types of activity. They were able to successfully identify thermal features with a 93% accuracy when compared against manual inspections. This paves the way for the development of an automated thermal analysis system to be applied on a global scale to future TIR missions such as the surface biology and geology (SBG) mission. Thompson et al., (2023) dug deeper into the expectations and prospects for quantitative volcanology in the upcoming era of new MIR/TIR satellites with a focus on SBG. They observe that the increased spatial resolution, saturation temperatures, and the addition of two MIR bands will improve thermal feature and spatial variability detection across all volcanic surfaces, as well as limit data saturation over high temperature targets such as lava flows. However, they are concerned that the number and placement of the TIR bands will impact the ability to accurately obtain spectral information from volcanic surfaces as well as geologic surfaces in general. They include suggestions that can be used to improve the SBG mission before development or could be considered in future MIR/TIR missions.

A significant amount of volcanic activity on Earth occurs as submarine eruptions. These eruptions can have an impact on the atmosphere, create ashfall, tsunamis, and pumice floating rafts that can be hazardous to ships and coastal infrastructures. However, understanding, characterization, and monitoring these eruptions is still early in its developmental stages due to their submarine locations. Fauria et al., (2023) studied the 2 August 2021 eruption of Fukutoku-Oka-no-Ba, a shallow submarine volcano in the Izu-Bonin arc of Japan to assess its eruption timeline, style, rates, and products using Himawari-8 and DigitalGlobe data. They determined the plume volume flux and height through time, the timing and mechanism of pumice raft formation, and concluded that the 0.1 km3 raft and eruption plume were co-genetic. The authors suggest that the pumice clasts were delivered to the raft by tephra jets, ballistics, and near-vent fallout from the plume. This is a step forward for submarine volcanology and leads the way in submarine eruption research.

The Hunga Tonga—Hunga Ha’apai (HTHH) eruption sequence that occurred in Tonga from December 2021 to January 2022 was remarkable in that it generated an explosion of historic magnitude that was preceded by ∼1 month of Surtseyan eruptive activity and two precursory explosive eruptions that generated extensive laterally spreading umbrella clouds. Gupta et al, (2023, Nature) performed an in-depth analysis of the eruption chronology of this eruption sequence using Himawari-8 geostationary satellite data. They evaluated the cloud top heights, longevities, water contents, and volumetric flow rates of the umbrella clouds and found the satellite-derived volumetric flow rate for 15 January 2022 of ~5.0×1011 m^3/s was nearly two orders of magnitude higher than the volumetric flow rates estimated for the 19 December 2021 and 13 January 2022 eruptions. Carn et al., (2022) studied the SO_2 emissions from this eruption using many different UV data sources including OMI and OMPs. They found vigorous SO_2 emissions prior to the January 2022 eruptions, providing strong evidence for a rejuvenated magmatic system. They also performed the first UV-based analysis of umbrella cloud spreading and volume flux during the 13 January 2022 eruption, and made connections to how submarine eruptions produce lower amounts of SO_2. This is impactful in that it provides additional information about pre-eruptive volcanic activity, SO_2 spreading modeling, and submarine volcanism mechanics. Van Eaton et al., (2023) studied lighting rings and gravity waves associated with the 15 January eruption plume using visible and infrared GOES-17 and Himawari-8 data. They found that the lightning rings expanded with enormous gravity waves in the umbrella cloud caused by buoyant oscillation of the overshooting plume top. These findings demonstrated that a sufficiently powerful volcanic plume can create its own weather system, sustaining the conditions for electrical activity at heights and rates not previously observed and that lightning data provides a valuable tool for monitoring and nowcasting hazards of explosive volcanism.

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. Molan and Lohman (2023) developed a pattern-based strategy for InSAR phase unwrapping and applied it to two fast-moving landslides in Colorado acquired by UAVSAR. Due to the high displacement rates of these two landslides, InSAR observations acquire longer than 7 days apart almost always fail when traditional unwrapping approaches are applied. However, they demonstrated, by validating their results against independently made measures, that their approach can perform this unwrapping reliably for much longer time intervals. Dandridge et al., (2023) performed a spatial and temporal analysis of landslide reporting on a global scale from 2007 to 2018 using NASA's global Landslide Catalog (GLC). They identified global patterns in the spatial and temporal distribution of landslide events as well as the associated casualties. Landslide "hotspots" were found in the Pacific Northwest of North America, High Mountain Asia, and the Philippines also the relationship between country GDP and income status with landslide occurrence was determined to have a positive correlation between economic status and landslide reporting was a bias toward English-speaking countries. The researchers provided these results in an effort to demonstrate how this database can be used for rainfall-triggered landslide research.

Tsunamis

Tsunamis are directly impacted by and can originate from solid-Earth related triggers. Melgar et al. (2022) examined the 2021 Acapulco earthquake using GNSS, tide gauge and InSAR data to determine what mechanisms lead to tsunami amplification. They determined that the 2021 earthquake and resulting tsunami was strikingly similar to the 1962 event and that a complex interaction of shelf modes and edge waves within Acapulco Bay continuously re-excite the bay resonance leading to a protracted tsunami. This work identifies the effect local water bodies and sea/lake floor shape can have on tsunami production. Song et al., (2023) used earthquake inversions from seismographs, radar, and optical data to study how the strike-slip movement of the 2018 Palu earthquake led to a subsequent tsunami. The general belief is that tsunamis occur only as the result of lateral movements of the seafloor or landslides. However, their experiments revealed that the motion of the east plate was responsible for pushing its overlaying water southward which generated a long-wave tsunami and inundated Palu city. The study suggests that tsunami triggering behavior is more complex than previously considered and should be accounted for in future tsunami early warnings.

Han et al., (2023, Eos) discussed how atmospheric waves measured from GNSS and CubeSat data can be used as an early warning for tsunamis in addition to the ocean buoy and tide gauge system currently in place. These systems can detect Lamp waves in the atmosphere that occur as a result of intense disturbances in the atmosphere from events like a volcanic eruption or tsunami. They travel significantly faster than ocean waves, about 315 m/s. These waves reach the ionosphere and produce traveling ionospheric disturbances (TIDs) which can be measured by GNSS sensors. The authors suggest a global constellation of numerous CubeSats could monitor 100 GNSS stations continuously for TIDs and provide identification and advanced warning of extreme events like tsunamis, volcanic eruptions, earthquakes, large storms, and even human-made explosions across the globe.

Cascading Hazards

Often the occurrence of one natural hazard can lead to the triggering of a single or several new natural hazards, we refer to this as a cascading hazard. Sattar et al., (2022) studied how a small Himalayan glacier lake outburst flood (GLOF) resulted in a much larger transborder flood as well as a debris flow. These GLOFs typically occur at high altitudes and can flow with an enormous amount of energy producing a change in the existing morphology. They examined the 5 July 2016 Gongbatongsha GLOF, a small water body that was triggered from heavy precipitation, absorbed sediment from previous landslides as it flowed downhill and produced a debris flow. This debris flow was deposited into a larger lake, this resulting rapid increase in water pressure breached a moraine dam which subsequently rapidly drained the entire lake. This flood produced an estimated >70 million USD in infrastructure damages and demonstrates the importance of considering the larger system of influences that may lead to a natural hazard when performing hazard monitoring and mitigation.

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. 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].

Mass Change

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.

Weise et al., (2022) lead the mass change designated observable study to recommend an observing system and present other key findings. They created a Science and Applications Traceability Matrix (SATM) with 15 science and applications objectives to establish the motivations for the mission and link desired scientific and practical objectives to recommended measurement parameters that will drive mission design and data system decisions. Many architectures were considered for this designated observable but in the end the team recommended an architecture similar in nature to its two predecessor missions: the Gravity Recovery and Climate Experiment (GRACE), and GRACE Follow-On (GRACE-FO). This will provide continuity with previous missions and provide a pathway for improved resolution and accuracy in resolving mass change. Tucker et al., (2022) performed a simulation of future improvements to satellite laser ranging (SLR) measurements that could improve time-variable gravity estimates in the low-degree gravity field. They found that a new SLR satellite can further support mass change observations by increasing the accuracy with which we estimate large-scale monthly gravity signals.

Vertical Land Motion

Sea level change is an increasing concern to island communities and locations that have many assets along the coast. These concerns can be exacerbated by vertical subsidence or improved by uplift; this is measured as vertical land motion (VLM). VLM is caused by either tectonic activity or by the loading of the crust from anthropogenic infrastructure and the occurrence of natural features such as glaciers, lakes, groundwater, and mountains. By understanding the extent and locations of VLM we can better understand how sea level change will impact the future. Huang and Sauber (2022) performed a study on Tutuila Island in the American Samoa by mapping VLM using persistent scatter (PS)-InSAR acquired from Sentinel-1A. PS-InSAR was used to capture local and regional deformation patterns despite the challenge the highly vegetated area poses for InSAR data collection. They found a region directly north of the ASPA GPS station to be subsiding more quickly than the rest of the island with the central portions subsiding the least, however all observed points on the island appear to be subsiding at a rate of at least −5 mm/yr. The authors point out that further work is needed to resolve discrepancies between the estimated deformation rate and GPS data and to better understand the ability of InSAR to accurately capture the regional differences around the island. This would include a comparison with tide gauge measurements in Pago Pago Harbor. Huang et al., (2023) returned to this study by observing six-year trends in VLM on Tutuila Island from late-2015 to mid-2022 using GPS, PS-InSAR, and joint tide gauge/satellite altimetry data. With this 6-year, more comprehensive study, they found that most of the populated areas on the island are subsiding at rates of 6–9 mm/yr with uncertainties of <1 mm/yr. The highest rates of deformation occur along the coastlines with strong areas of subsidence at Pago Pago International Airport and Pago Pago Harbor. These findings suggest that for effective flood forecasting officials require a comprehensive understanding of diverse contributions leading to local subsidence.

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 and the Decadal Survey Surface Deformation Mission, currently in study phase. Connected to this is enabling research for SAR/InSAR, as well as for complementary techniques built on GNSS/GPS geodetic data.

Researchers regularly seek methods to improve the accuracy of geodetic data acquired in different situations. Wang and Chen (2022) developed a method to improve the accuracy of identifying persistent scatterers using plane similarity of radar pixels. Their method uses an algorithm based on the similarity of phase observations between nearby radar pixels. This algorithm reduces the number of false positive and false negative PS pixels when compared against existing PS identification algorithms, additionally the improved PS identification accuracy allows us to substantially increase the total number of high-quality interferograms that are suitable for time series analysis. This method can be used to reconstruct spatially coherent InSAR phase observations through an interpolation between PS pixels and recovers subtle deformation signals that are otherwise undetectable. Zebker et al., (2023) sought to quantify tropospheric noise and surface deformation signals for InSAR study sites that do not have GPS measurement available for validation using common-reference interferogram subsets. They validated all results with independent GPS tropospheric zenith delay and surface deformation time series data with sub-cm RMS errors. They determined that tropospheric noise is non-Gaussian and follows a seasonal pattern and that the propagation of tropospheric noise leads to up to ~5 cm of false deformation signal when deriving either a stacking or Small BAseline Subset (SBAS) time-series solution.

NASA-ISRO Synthetic Aperture Radar (NISAR) Science Team

The NISAR project coordinated a NASA review of the algorithm theoretical basis documents (ATBDs). A significant finding from the Ecosystems review team stipulated that the algorithm does not go far enough to highlight the true potential of the NISAR data set – that other more modern algorithms based on machine-learning techniques could produce more accurate results over a broader range of biomass. The Science Team is taking this finding into consideration by offering the standard algorithm, which is sufficient to meet requirements and known to be robust over a variety of land cover types, as well as offering other experimental methods.

The NISAR Project conducted several workshops over the year. The first was a community workshop held at the Pasadena Convention Center in Pasadena, CA on August 30-September 1, 2022. This was the first major in-person NISAR science event since the global pandemic, and over 300 enthusiastic researchers across a broad demographic attended. The goal of the workshop was to prepare the community for the NISAR mission by highlighting the expected products, the data access mechanisms and formats, the science algorithms and tools being provided by the science team, and the opportunities for collaboration and funding. Plenary talks by NASA and project officials, project team members, and science team members provided a broad overview of the mission capabilities, timeline, and science and applications potentials. Poster sessions provided an opportunity for the community to demonstrate how they intend to use NISAR data, and to interact with others to share ideas for new science. The feedback from participants was positive; many continue to participate in NISAR Science Town Hall virtual meetings held in conjunction with Science Team meetings

A NISAR workshop on Severe Weather Hazards at USGS Headquarters was held in Reston VA May 10-11, 2023. The workshop brought together participants from organizations working in emergency management at the local, state, and national level as well as academia, NASA headquarters and the NISAR Science Team to discuss the potential of NISAR for severe weather mapping. The participants had a broad range of experience with remote sensing data, and were predominantly associated with flood hazard prediction, monitoring and mitigation. SAR is an effective tool for flood mapping because the signature of flooding is relatively clear in SAR imagers. Its measurements are largely unaffected by clouds, so it can reliably monitor floods through rain events. NISAR's plan of regular acquisitions over all land surfaces of twice per week was viewed by participants as a significant addition to existing means of monitoring flood events.

Following the success of the 2020, 2021, and 2022 UNAVCO virtual training classes for geodetic imaging, members of the NISAR project science and algorithm development team will repeat the training in August 2023. This year again, 150 students have been selected out of a pool of over 500 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 instructor pool has been increased to broaden community engagement and provide better interaction with the students.

The Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) Facility

During the time period from July 19, 2022 to June 30, 2023, UAVSAR conducted 46 science and engineering flights totaling 270 flight hours. All flight lines were acquired in the United States and Canada: 351 flight lines were imaged with the L-band radar, 60 flight lines with the P-band radar, and 44 flight lines with the Ka-band radar. The Project supported 16 Principal Investigators (PI) performing research on a broad range of Earth Sciences disciplines: Applied Sciences, Hydrology, Earthquakes, Landslides, and Terrestrial Ecology. The UAVSAR team additionally conducted engineering flights for instrument calibration, and responded to 1 Rapid Response event: Hawaii's Mauna Loa volcano eruption.

Xu et al., (2023) used UAVSAR to acquire P-band repeat-pass SAR data to assess hazards of densely-vegetated deep-seated (DVDS) landslides over the Pacific Northwest. Observations were used to derive landslide characteristics such as along-slope motions and build hazard maps using state-of-art landslide runout and inundation dynamics models. This study found that P-band outperforms L-band data for discovering deformation in densely vegetated terrain as the authors identified over 200 new landslides that were missing from existing inventories. This new information will help provide a more complete knowledge base for understanding hazards of DVDS landslides over the Pacific Northwest.

UAVSAR was tasked to image Mauna Loa Volcano shortly during the December 2022 eruption. Ka-band TopSAR (GLISTIN-A) and SAR-Fusion (visible+SWIR) instruments aboard the AFRC C-20 jet were flown on Dec. 7, 8, 10 and processed DEMs were delivered within 2 days after the first flight. USGS scientists used the differential DEMs to derive lava thickness and update lava flow model to predict lava flow rate in support of the state's hazard response.

Next generation UAVSAR planning is well underway, it will be rebranded as AIRSAR-NG as it will be flying on a Gulfstream class jet. The current plan is to transition to a Gulfstream-IV jet that is more reliable, slightly longer range, and capable of housing L-band and P-band antennas to facilitate simultaneous P/L-band data acquisitions. This will enable future science campaigns that demand both frequencies, and support future decadal survey observation development such as Surface Deformation and Change and Surface Topography and Vegetation incubation activities. New technology development via the FlexDSAR IIP is underway to facilitate a flexible and reconfigurable compact radar suitable for synthesizing large antenna aperture across multiple CubeSat/SmallSat platforms. This software defined radar front-end electronics for digital beamforming will serve as the backbone of the AIRSAR-NG's radar electronics.

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.

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.

Multi-GNSS operations continued with the operational production of daily, low rate (300 second) Galileo + GPS orbit and clock products. Effort has been focused on Galileo since it has been shown that the combination of GPS + Galileo produces benefit over GPS alone in Precise Point Positioning. Special "prototype" high rate (30 second) GPS + Galileo products were provided to the SWOT mission to improve the positioning of dynamic calibration targets during the mission's calibration/validation phase. This effort sets the stage for operational production of high-rate GPS + Galileo products in the coming months. These products promise benefits for positioning dynamic platforms and for users interested in using GNSS to observe Earth's atmosphere and ionosphere. The long-term goal is to produce products from all four major GNSS constellations for distribution to NASA missions and researchers. Development of multi-technique capabilities also enjoyed success. Satellite Laser Ranging (SLR) data analysis capabilities have been used with GPS capabilities in TRF research and shown good results. Very Long Baseline Interferometry (VLBI) capabilities reached a breakthrough and showed good comparisons with results from other software using similar data inputs. The capability to analyze data from multi-technique networks is supporting a major research effort in developing terrestrial reference frame solutions, described below.

GDGPS

GDGPS is transitioning from support of commercial users/sponsors to the distribution of products and services to the public and targeted to support of NASA researchers and missions. This transition involves converting to standard product formats and distribution through the NASA's Crustal Dynamics Data Information System (CDDIS) which provides free public access to the community. In addition, GDGPS is developing software and enhancing service that combines the user's GNSS measurement with real-time GDGPS corrections to provide high-precision real-time point positioning. GDGPS is also collaborating with the EarthScope Consortium which will use GDGPS real-time corrections to validate PPP products from other solution providers for ShakeAlert seeking to provide earthquake early warnings. In the past year, GDGPS has partnered with the International GNSS Service Central Bureau (based at NASA JPL) to promote and advocate for use of GDGPS in disaster risk reduction applications. This has included establishing a Task Force on GNSS for Disaster Risk Reduction under the UN International Committee on GNSS (ICG).

NASA Space Geodesy Network

The NASA Space Geodesy Network (NSGN) stations continued to operate, maintaining or exceeding levels of scientific data output achieved in prior years. In 2022, the 7 NASA SLR station network tracked three classes of Earth satellites: (i) Low Earth Orbit (LEO), science-related satellites, (ii) geodetic satellites whose data support development of the International Terrestrial Reference Frame and low degree harmonics of the Earth's gravity field such as LAGEOS-1, LAGEOS-2, LARES and the Etalon satellites, and (iii) GNSS satellites. NASA SLR stations supported scientific satellites including ICESat-2, Jason-3, Sentinel-6A/Michael Freilich, GRACE Follow-On & SWOT, and missions by partner space agencies that supply key scientific data including CryoSat-2, Sentinel-3A & 3B, and the Swarm constellation. SLR data to Sentinel-6A showed that in 2021 and 2022, the average Root Mean Square (RMS) radial orbit error for the mission's precise orbit products was 7-9 mm. SLR data to SWOT have shown that the radial orbit quality produced from the GNSS tracking data is 1.5 cm RMS, within the mission specifications.

SGP continued to advance the next-generation VLBI Global Observing System (VGOS) by operating its broadband VLBI stations at Kōke'e Park Geophysical Observatory (KPGO) in Hawaii, at the Goddard Geophysical and Astronomical Observatory (GGAO) in Maryland, at the McDonald Geodetic Observatory (MGO) in Texas, and at Westford in Massachusetts. The 2-station VGOS UT1 (Universal Time) "Intensives" program between KPGO and Wettzell, Germany, that measures the variation in the rotation rate of the Earth, expanded to five sessions a week and demonstrated better performance than the legacy S/X Band VLBI Intensives. These VGOS INT sessions used an improved scheduling strategy after January 31, 2022, that increased the number of observations obtained in a 1-hr session. Fifteen months of sessions five days per week (January 2022 – March 2023) were evaluated and shown to provide comparable or improved performance compared to the products from the VLBI legacy Intensive sessions.

Terrestrial Reference Frame Combination

A JPL produced Terrestrial Reference Frame solution, JTRF2020, using Geodetic network solutions from the four major Geodetic techniques was completed. The NASA/JPL approach to Terrestrial Reference Frame (TRF) determination 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. The current JPL TRF solution is the first full solution produced using the new, "SREF" (Square-root Reference frame Estimation Filter), software. JTRF2020 will form the basis for regular updates, which are expected to begin in late 2023 or early 2024. JTRF2020 and updates, when available, can be found on JTRF Website, www.jpl.nasa.gov/site/jsgt/jtrf/.

JPL is also performing cutting edge research in Terrestrial Reference Frame solutions by directly analyzing observations from Space Geodesy techniques and other sources, rather than combining the results of network solutions from each technique. Recently developed VLBI analysis capabilities in GipsyX software are being used to combine VLBI observations with GPS ground, GPS flight, and SLR observations into an experimental TRF solution. VLBI observations provide unique information on the Earth's orientation in space and are complementary with observations from the other Geodetic techniques. Interim TRF solutions compare favorably to those from ITRF2020, the international standard. If ultimately successful, this approach could drastically reduce the cost of maintaining a high quality TRF. Unlike the current approach to the ITRF, a high quality TRF solution could be maintained by a single analysis center, instead of the ~ 30 currently required, and minimize the need for expensive ground stations, such as those required for SLR and VLBI measurements.

SGP International and Interagency Cooperation

The NASA Space Geodesy Program (SGP) continues to be a key participant in the United States Delegation to the United Nations Committee of Experts on Global Geospatial Information Management's Subcommittee on Geodesy. The US Delegation is an inter-agency collaboration led and coordinated by the Census Bureau (Department of Commerce) and supported by other US geodesy-stakeholders. UN efforts to establish a UN GGIM Global Geodetic Centre of Excellence have advanced in the past year with the opening of the Centre at the UN Campus in Bonn on 29 March 2023, and supported by a public GGIM Global Geodesy Forum. The Centre of Excellence will provide internationally funded staff for dedicated advocacy and assistance to nations wishing to invest in geodetic infrastructure and capacity development.

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, drawing upon efforts from across the entire Earth Science Division, aims to resolve all fluxes of water (between land, ocean, and atmosphere) 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.

THP is responding to the 2017 Decadal Survey (DS-2017) with investments to better resolve and understand snow albedo, related to observables of the Surface Biology and Geology (SBG) mission. THP is also preparing snow algorithms and understanding to support opportunities provided by the upcoming NISAR and Surface Deformation and Change (SDC: the mission that will follow NISAR) and for the DS-2017 identified Snow Depth and Snow Water Equivalent Explorer mission. THP is also exploring new DS-2017 opportunities with both the PBL (Planetary Boundary Layer) and STV (Surface Topography and Vegetation: i.e. water routing) Incubation Studies.

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 upcoming missions (i.e. 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 FY2023 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 three papers that highlight water cycle and water extremes measured by the GRACE and GRACE-FO missions. Next are two papers that discuss how floods and droughts impact food security. The Water Budget and Water Cycle Dynamics section of the report showcase WEC's research in snow, surface water, High Mountain Asia, soil moisture, and groundwater. The second section of 1.1.8 titled 'Water – Hazards / Ecosystem / Evapotranspiration / Drought / Wildlife / Water Quality' describes new water related research that spans the hydrosphere and ecosphere.

Satellite remote sensing has revolutionized the global measurement of the water cycle and its components. This becomes more important as climate change leads to more extremes (e.g., floods, droughts, fires). The Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE/FO) missions have emerged as the primary sources of global observations of terrestrial water storage (TWS), which is an 'essential climate variable' (Rodell and Reager, 2023: *Nature Water*). Retrieved TWS has been used to validate hydrological models and to help monitor groundwater, both societally important contributions. The routinely-delivered GRACE-based soil moisture and groundwater drought/wetness indicator enables GRACE data to be useful for operational drought monitoring. The weekly, near-real-time availability was particularly important for drought, water resources and agricultural decision-makers. GRACE/FO data assimilation was expanded to all continents except Antarctica, serving as the basis for unprecedented weekly, global root zone soil moisture and groundwater wetness/drought indicator maps. Both wet extremes (e.g., flooding) and dry extremes (drought) are quantified using GRACE.

Hydrologic extremes often involve a complex interplay of several processes. Models alone are limited in their ability to simulate the variations and complexity of these interacting processes. Remote sensing has a key role in accurately representing these processes (e.g., snow, snowmelt, surface water, flooding) and their impact on agriculture. A recent study by Lahmers *et al*. (2023: *Scientific Reports*) demonstrated that incorporating remote sensing of hydrological information within models improves the accuracy of soil moisture by up to 16%, snowmelt by 24%, and also improves the simulation of vegetation extremes. This study demonstrated how data assimilation (DA) of multivariate and multi-sensor remote sensing datasets help in capturing the drivers and impacts of the 2019 Midwest floods. Looking ahead to the coming year, assimilation of data from the recently launched Surface Water and Ocean Topography (SWOT) mission could help contribute streamflow data in the future.

A regional study of extremes by Rodell and Li (2023: *Nature Water*), applied a novel approach with terrestrial water storage observations from the GRACE and GRACE-FO satellites to delineate and characterize 1,056 extreme events during 2002–2021. They found that the largest event identified was an ongoing pluvial that began in 2019 and engulfed central Africa. The magnitude was such that Lake Victoria rose over 1 m, with flooding in the surrounding region. The second largest event was a 2018-2021 pluvial over central and eastern North America. The third largest event was a 2011-2012 Australian pluvial that ended the Millennium Drought and even caused sea level to decline for a brief period. Also, they found the intensity of extreme water events was strongly correlated to high terrestrial soil temperatures, suggesting that continued warming will cause more frequent, more severe, longer and/or larger droughts and pluvials (floods).

The 20-year data record of GRACE (with GRACE-FO) enables identification and quantification of extreme hydroclimatic events globally from TWS anomalies, which was not previously possible. Ongoing and future events will continue to be assessed with GRACE-FO and the proposed Mass Change mission. This is important given the finding of Rodell and Li (2023: *Nature Water*) that the global monthly intensity of extreme hydroclimatic events is increasing with global warming. This is consistent with the IPCC Sixth Assessment Report which has medium-to-high confidence that the severity of extreme water cycle events is increasing.

Hydrologic extremes, both flood and drought, have major impacts on global food security. The National Academies report by Reed *et al*. (2022: *PNAS*) articulated that floods impact food security for ~12% of modeled African population that experienced food insecurity during our study period. Flood impacts on food security vary depending on scale, with declines likely at smaller scales but mixed impacts at national and regional scales. Improved data collection at the intersection of flooding and food security, and at the spatial scales ranging beyond conventional humanitarian responses, is critical to better mitigate food security impacts of flood disasters across Africa and globally.

One tool that NASA provides to deliver information on food security is the Soil Moisture Active Passive (SMAP) mission. Krishnamurthy *et al*. (2022: *Nature Sustainability*) demonstrated that SMAP retrievals of soil moisture, integrated with food prices, provides an early warning for food crises caused by droughts months in advance. They analyzed drought-induced food crises globally in the SMAP record (since 2015; approximately five per year). The change in soil moisture autocorrelation led to a dramatic improvement in anticipating the timing and intensity of food crises, with lead times of up to 3 to 6 months for every case. This is a significant advancement in the capabilities of food security early-warning diagnostics and could save lives and resources. Furthermore, this study is the first documented analysis of a relationship between the autocorrelation indicator and the magnitude of the change in food security, suggesting that in the future, the response could be predictively scaled to anticipate the size of the food crisis.

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: 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 the newly commissioned SWOT) and new research supporting missions that are in development (i.e., 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 reviews selected publications in the following sections: Snow, Surface Water, High Mountain Asia, Soil Moisture, and Groundwater.

Snow

SnowEx is a multi-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. This need was amplified by the 2017 Decadal Survey that identified snow water equivalent and snow depth as potential observables for an explorer-class mission. As such, SnowEx 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. More than one-sixth of the world's population relies on seasonal snowpack and glaciers for a water supply that is likely to decrease this century. Snow is also a critical component of Earth's cold regions' ecosystems, in which wildlife, vegetation, and snow are strongly interconnected. Snow water equivalent (SWE) describes the quantity of water stored as snow on the land surface and is of fundamental importance to water, energy, and geochemical cycles. The following five publications highlight some of the snow related research, starting with two on snow science, a pair on freeze-thaw, and a high-impact paper on a satellite study of permafrost thaw, which is a major impact of climate change.

Bair *et al*. (2023: *The Cryosphere*) examines trades between spatial resolution (30-m) and temporal resolution for snow retrievals. This is important for scientific studies ranging from hydrology to wildlife biology. As validated by the Airborne Snow Observatory (ASO), Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover and snow albedo from MODIS provide accurate forcings for snow models. The future of Earth snow observations is satellite constellations and fusion techniques that provide higher resolution, both spatially and temporally.

Given the limitations of existing spatial and temporal resolution of snow remote sensing, Tsang *et al.* (2022: *The Cryosphere*) reviews the potential contribution of X- and Ku-band synthetic aperture radar (SAR) for global monitoring of SWE. Advances in the last decade have improved SAR retrieval algorithms for snow because of dedicated field observations, physical snow modeling, electromagnetic theory and retrieval strategies over a range of physical scales. For example, the Canadian Space Agency is planning a mission around a dual-frequency Ku-band Terrestrial Snow Mass Mission (TSMM) concept. The authors identify a clear need for more experimental snow measurement campaigns to fill information gaps, but see continued development of satellite missions with Ku-band radar and synergistic techniques for better global measurements of SWE.

Freeze-thaw (FT) status is a viral component of land surface models, becoming increasingly important during rapid warming and thawing of permafrost. Walker *et al*. (2022: *IEEE Trans. Geosci. Remote Sensing*) demonstrates a hidden Markov model (HMM) to retrieve FT from combined L-band Soil Moisture Active Passive (SMAP) and Ka-band Advanced Microwave Scanning Radiometer (AMSR) satellite microwave brightness temperatures. Three states are identified, frozen, thawed and in-between. The study focuses on latitudes north of 45 N, including the high-interest areas of the arctic and boreal landscapes.

Moradi *et al.* (2023: *Cold Regions Science & Technology*) examined a nine-member ensemble with combinations of 3 land surface models (LSM) and 3 meteorological models or data assimilation systems to assess winter processes such as annual minimum temperature, number of frozen days and freeze/thaw (FT) cycles. They found models overestimating the annual number of frozen days and FT cycles, while underestimating the minimum temperatures.

Webb *et al.* (2022: *Nature Climate Change*) utilized the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite-based superfine water index (SWI) to quantify surface water change across lake-rich regions of the Arctic over the past two decades. They found large-scale drying of lakes in Arctic lowlands over the past two decades. Increasing air temperature and autumn precipitation lead to permafrost thaw, which leads to widespread surface water decline (drying). This is important because changes in surface water affect fresh water availability, wildlife, land surface albedo (for climate), and the carbon cycle.

Surface Water

WEC has invested in improving our ability to resolve surface water extent and measure river discharge, with added focus on preparing for SWOT. Both of these topics (surface water in storage and in transit) are important 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. The Surface Water section begins with five publications covering a different elements of surface water hydrology and is followed by a pair of publications on SWOT.

David *et al.* (2023: Nature Geoscience) highlight the importance of previous studies from Basso *et at* (2016: Geophysical Research Letters) where they approach the threat of extreme flooding events increases as global warming intensifies. The study of floods includes analysis of the distribution of hydrological properties such as rainfall, river's season maximum height, or flow rate. As the probability of flood occurrence decreases, the potential for catastrophe increases. The flood divide is a recent concept essential to determine the risk of significant flooding. A drastic shift in the distribution of hydrological variables correlates with extreme floods larger than expected. The model's simplification identifies two essential parameters: the hydrograph recession exponent and the coefficient of variation of daily flows. The former determines the river basin's drainage rate linked to the river's morphology. The latter quantifies daily flow fluctuations of the river basin mean flow (i.e., correlations between precipitation, evapotranspiration, soil moisture, and precipitation response time). Catastrophic flooding is not solely a product of precipitation and storage conditions. However, it also depends on the intrinsic properties of river basins (flood divide), allowing us to forecast flood risk based on past conditions.

Flooding disaster response can be monitored through satellite remote sensing due to its comprehensive coverage and real-time monitoring capabilities. Tulbure (2022: ISPRS Journal of Photogrammetry and Remote Sensing) focuses on enhancing flood detection using combined observations from Landsat-8 (L8) and Sentinel-2 (S2) satellites. This fusion and machine learning improve surface water and flooding extent mapping, particularly for ephemeral flooding events, and captures the maximum extent of large floods. The research maps flood dynamics, assesses accuracy, and evaluates the enhanced temporal frequency of the Harmonized Landsat-8 Sentinel-2 (HLS) compared to a single observation for detecting ephemeral floods in the Australia Murray-Darling Basin (MDB). The first flood prediction approach employs data-driven statistical models using river flow and climate data to predict flooding, even between cloudy Landsat observations. The second approach involves satellite data fusion, like blending Landsat and MODIS data with algorithms such as spatiotemporal fusion. However, both methods struggle to detect ephemeral floods due to blending's inability to capture dynamic, ephemeral floods and the statistical model's assumption of consistent flood distribution. Results demonstrate the significance of harmonized multi-sensor data like the HLS for effective land monitoring, presenting a pioneering use of HLS data for flooding assessment.

The California Central Valley supplies a quarter of the US food, relying on water from surrounding mountains for irrigation. Recent periods of droughts and heavy precipitation have impacted the region. Argus *et al*. (2022: *Geophysical Research Letters*) used GPS and NASA's GRACE missions, to track temporal water storage availability in the Sacramento-San Joaquin-Tulare basins and the California Central Valley. This study was able to identify when the maximum quantities of snow, soil moisture and groundwater occurred and how their oscillation varied within the drought or heavy precipitation periods.

Bonnema *et al*. (2022: *Geophysical Research Letters*) focused on improving our understanding surface water bodies (SWBs) by using diverse data sources and methods. Previous databases relied in optical observations with cloud coverage limitations, hampering seasonal observations. This study employed Sentinel-1 synthetic aperture radar data to overcome cloud barriers and examine flooding and water coverage changes. By analyzing vast SWB data, Google Earth Engine water probability maps, and Sentinel-1 observations, the study developed algorithms for global SWB classification, revealing insights about over 150k lakes and reservoirs. Results highlighted that size and natural/artificial origin can influence the water body dynamics. Temporal variations in both lakes and reservoirs were observed, with reservoirs showing higher fluctuations. Smaller SWBs exhibited higher variability (~74%) compared to large bodies (>10,000 km2). The study's findings contribute to understanding global water-land dynamics in seasonally inundated SWBs.

The Amazon basin serves as a crucial ecosystem for the planet, providing sustenance to humans through food and resources. Fleischmann *et al*. (2023: *Environmental Research Letters*) used hydrological models, in-situ river gage measurements, and satellite observations to study the behaviors of the floodplains of the Amazon river in the lower lands. The results indicate a 26% increase in the central Amazon's annual inundation extent since 1980, highlight rising water levels and 65% longer flood durations. Climate change effects will have uncertain repercussions, and shifts in rainfall and simultaneous droughts and floods require further investigation. The ramifications of such changes span floodplain ecosystems, geomorphology, biogeochemistry, and human populations dependent on them, necessitating enhanced mitigation strategies from local to international levels to ensure resilience and mitigate damage.

SWOT Science

The SWOT Mission is expected to significantly increase our understanding of river flow rates in ungauged basins, and water storage in lakes and 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. SWOT is starting to fulfill its promise as a revolutionary source of information about surface water. Having completed its three-month commissioning phase, SWOT entered a three-month calibration phase. On July 21, 2023, the spacecraft moved into its science orbit. We are looking forward to reporting on the initial SWOT findings as data become available during the FY24 GPRA cycle

Long-term and real-time river discharge records streamflow are necessary for effective freshwater resource management, but challenges like limited data availability and damaged instruments exist in the current publicly available datasets. The utilization of near-real-time discharge measurements using satellite imagery enhances river monitoring. Despite difficulties in accessing complete and continuous public data, Riggs *et al.* (2023: *Environmental Research Letters*) study compiles and analyzes a dataset of global river gauge records spanning 1900 to 2021, revealing trends and gaps via the gauge record completeness (GRC) variable. The study emphasizes how historical events and socio-political factors can impact the GRC, and satellite observations complement gauge records, aiding in improving river flow measurements. The researcher developed a rating curve function as a means to enhance measurement latency and estimate discharge through direct satellite observations, without the need for extensive hydrological modeling.

SWOT aims to produce a significant data product, river discharge, for previously data-scarce or unreliable river locations worldwide. Durand *et al.* (2023: *Water Resources Research*) outlines the accessibility of SWOT data through the American and French space agencies, presenting a detailed methodology divided into sections. The methodology involves estimating river discharge from raw data, determining flow law parameters, segmenting observation into 10 km sections, bounding estimates with in-situ gage measurements, and model fitting. SWOT results will be compiled into a comprehensive river database, including spatial sampling and temporal discharge characteristics. This achievement allows SWOT to accurately estimate streamflow variations, providing flow maps for global basins, enhancing our understanding of global hydrological processes.

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 in the spring of 2021 and new research is underway.

High Mountain Asia (HMA) has the largest expanse of snow outside of the polar regions and it plays a critical role in climate and hydrology. In situ monitoring is rare due to terrain complexity and inaccessibility, making remote sensing the most practical way to understand the hydrology of HMA. Two papers highlighted here study HMA precipitation and rain-on-snow, and how those impact water supplies for South Asia.

Maina *et al.* (2022: *Journal of Hydrometeorology*) developed an ensemble consensus for precipitation estimates over High Mountain Asia using a localized probability matched mean approach. They found that this approach reduces biases and provides more realistic spatial patterns than a simple ensemble mean. This is important for regional water supply implications for multiple countries, and food supply implications for billions of people. Maina and Kumar (2023: *Earth's Future*) used a land surface model Noah-MP with an ensemble precipitation data set to study trends in rain-on-snow (ROS) over high Mountain Asia from 2001 to 2018. They found that increasing ROS over the Indus basin contributes to snowmelt, less snowpack and reduced water availability, while decreasing ROS over the Ganges-Brahmaputra leads to decreased recharge from the headwaters. Both may lead to overusage of groundwater, unless increasing trends in rainfall compensate for the decreasing snowmelt.

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 Soil Moisture Active Passive (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. Soil Moisture retrievals from the NASA Soil Moisture Active Passive (SMAP) are important for climate studies and applications including weather services (flood and drought forecasts), agricultural production (crop growth models), soil conservation, and landscape management. The highlighted publications below focus on water cycle science, advancements learned from SMAP, and an important soil moisture application.

Koster *et al.* (2023: *Nature Communications*) used surface (0-5 cm) soil moisture retrievals from the SMAP satellite instrument to show that late-fall satellite-based surface soil moisture estimates are strongly connected to springtime streamflow. Thus, satellite-based soil moisture retrievals have the potential to produce improved seasonal streamflow predictions several months in advance. A key advantage offered by SMAP is accurate soil moisture information (better than reanalysis) in poorly instrumented regions of the world.

Passive microwave remote sensing is considered the best tool for mapping spatial soil wetness, specifically from spaceborne L-band radiometers such as SMAP. One limitation of the Mironov 2009 physically-based dielectric model used for SMAP is that it does not account for soil organic matter. Zhang *et al.* (2023: *Remote Sensing*) performed a comparison of nine advanced soil dielectric models over organic soil in Alaska. Four of the nine models are shown to account for SOM, while the other five models are designed for use with mineral soils. Zhang *et al.* (2023: *Remote Sensing*) recommends the use of Mironov 2009 in the SMAP SCA-V algorithm for mineral soils (SOM < 15%), and Mironov 2019 for organic solids (SOM > 15%).

Du *et al.* (2023: *IEEE Sel. Topics J. Applied Earth Obs. and Remote Sensing*) developed a new global 1-km water mask for SMAP operations. The benefit of the updated water mask is greater in areas with substantial surface water heterogeneity, including coastlines, river floodplains, and reservoirs. The benefit is also greater in the Northern Hemisphere high latitudes, where the updated water mask is more effective in resolving the abundance of smaller water bodies in boreal and tundra wetlands.

Large uncertainties can be introduced in the retrieval of soil moisture due to the complexity of surface processes and measurement errors such as those resulting from the brightness temperature or radar backscatter. It is, therefore, necessary to verify satellite-based soil moisture products using in situ measurements. The retrieval of soil moisture under heterogeneous land cover, forest, and high-latitude regions remains a challenge for the SMAP mission. One of the objectives of SMAP extended mission is to validate soil moisture and vegetation optical depth retrievals in forested areas. Understanding the uncertainties that can be introduced in the retrieval of soil moisture in forested regions will contribute to the improvement of satellite-based soil moisture products in forested areas. Performance of Leve l2 SMAP enhanced soil moisture passive microwave product in a forest site was assessed by Abdelkader *et al.* (2022: *Remote Sensing*) in a comparison with in-situ methods. They found that performance of SMAP retrievals varied with season as surface conditions changed, with best performance in July through September (lower vegetation density), and degraded performance in March/April due to freeze/thaw conditions.

Ambadan *et al.* (2022: *IEEE Trans. on Geoscience and Remote Sensing*) evaluated SMAP soil moisture retrievals over a boreal forest in Canada by comparison with an in-situ network, identifying that – for dry soil – SMAP L2 SM products agree better with the in-situ lower mineral layer SM than the overlying organic soil SM. SM can be retrieved using the t-w model provided that vegetation and soil parameters are optimized.

Wang *et al.* (2022: *Int. Journal Applied Earth Obs. and Geoinformation*) investigated disaggregation of SMAP brightness temperature (TB) using RADARSAT-2 polarimetric decompositions to retrieve high-resolution SM over multiple spatial resolutions. They obtained the best retrievals at a spatial resolution of 50 m (R = 0.63–0.76 and RMSE = 0.046–0.067 m3/m3), which is useful to capture the spatiotemporal heterogeneity of SM within and among agricultural fields. This has applications in soil water management.

Rodriguez-Alvarez *et al.* (2023: *Scientific Reports*) validated the use of Global Navigation Satellite system – Relectometry (GNSS-R) by SMAP for added value SM products in area with high vegetation optical depth (VOD). A few months after SMAP's launch, the radar transmitter's high-power amplifier suffered an anomaly, and the instrument could no longer return data. During recovery activities, the SMAP mission switched the radar receiver frequency facilitating the reception of Global Positioning System (GPS) signals scattered off the Earth's surface, and enabling the radar to become the first spaceborne polarimetric Global Navigation Satellite System – Reflectometry (GNSS-R) instrument. SMAP GNSS-R data, with >7 years of continued measurements, are the most extensive existing GNSS-R dataset and the only one providing GNSS-R polarimetric measurements. They demonstrated that the SMAP polarimetric GNSS-R reflectivity, derived from Stokes parameters mathematical formulation, can enhance the radiometer data over dense vegetation areas, recovering some of the original SMAP radar capability to contribute to the science products and pioneering the first polarimetric GNSS-R mission.

It is amazing that remote sensing can provide inform on vector borne disease (VBD). Thomas *et al.* (2023: *Geophysical Research Letters*) used satellite-measured soil moisture data from SMAP to show that flooding in 2020 African Sahel was the most extreme flooding event in the region in forty years. The event was linked with disease outbreaks, and soil moisture is demonstrated as a better indicator of outbreak risk than precipitation alone, which was previously used. It is expected that future monitoring and prediction efforts for VBD risk will utilize SMAP soil moisture data.

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), GNSS, and altimetry all measure 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. .

Accurately measuring and monitoring groundwater storage and fluxes is critical for water, food, and energy security. Adams *et al.* (2022: *Water Resources Research*) review several state-of-the-art remote sensing techniques useful for local- to global-scale groundwater monitoring and assessment, including proxies for groundwater extraction. Remote sensing approaches such as gravitational measurements, InSAR, GNSS, lidar altimetry, and Airborne Electromagnetic Systems can yield indirect yet valuable information about groundwater. Fusing multiple remotely sensed data sets or employing other tools such as numerical models increase the applicability of individual approaches.

Groundwater is an important source of irrigation water, enabling resilience during drought. In the heavily agricultural Central Valley, California, groundwater management is being slowly implemented, but heavy use during drought has led to falling water tables, drying wells, subsiding land, and its long-term disappearance. Liu *et al.* (2022: *Nature Communications*) use nearly two decades of observations from NASA's GRACE satellite missions to show that the rate of groundwater depletion in the Central Valley has been accelerating since 2003, during a period of megadrought in southwestern North America. Results suggest the need for expedited implementation of groundwater management in the

Central Valley to ensure its availability during the increasingly intense droughts of the future.

Water –Drought / Hazards / Water Quality / Wetlands

This section contains WEC funded research that is outside of the water cycle but important component of the overall research portfolio. The thematic topics vary from year to year as research matures and there are sufficient number of publication to highlight. This year we are highlighting a diverse range of topics, as noted in the section title, that are broadly in response to climate change with too little/too much water and the implications on water quality and wetlands.

Drought

One of the primary sources of predictability for seasonal hydroclimate forecasts are sea surface temperatures in the tropical Pacific, including El Niño–Southern Oscillation. Analyzing observations and reanalysis covering twenty-five La Niña events, Anderson *et al.* (2023: *Journal of Hydrometeorology*) present results that provide a physical understanding of the sources and limitations of predictability when using multiyear La Niña forecasts to predict drought in the Horn of Africa, where multi-season drought has contributed to an ongoing food security crisis. They demonstrate that multiyear La Niña events favor drought in the Horn of Africa in three consecutive rainy seasons, but do not tend to increase the probability of a fourth season of drought owing to the sea surface temperatures and associated atmospheric teleconnections in the long rains season following second-year La Niña events. Increased subsidence over the Horn of Africa, associated with warmer waters in the west Pacific that enhance the Walker circulation, and enhanced cross-continental moisture transport, associated with a warm tropical Atlantic, in first-year La Niña events compared to second-year La Niña events, favors drought in the Horn of Africa.

Hall *et al.* (2023: *Earth and Space Science*) studied aridification in the Great Basin. Terminal lakes in the Great Basin (GB) of the western US host critical wildlife habitat and food for migrating birds and can be associated with serious human health and economic consequences when they dry out. Twenty-one years of satellite-derived data from the MODIS instrument enable Hall et al.'s unique way to evaluate effects of aridification and rising temperatures on terminal lakes and assess their individual vulnerabilities. Surface and air temperatures in the Great Basin are rising dramatically, with a sharp rise in the rate of increase observed beginning around 2011, and coinciding with fewer days of snow cover, a decrease of inflow to the lakes, and greater evaporation of water from the lakes. Evapotranspiration is generally lower in the Great Basin, exacerbated by drought restrictions on evaporation, likely reinforcing regional warming. Severe and costly ecological, human health and economic consequences are expected if the lakes continue to decline as predicted.

Using NASA satellite sensors of precipitation (Global Measurement Mission, GPM), soil moisture (Soil Moisture Active and Passive, SMAP), and terrestrial water storage (Gravity Recovery and Climate Experiment, GRACE), Lakshmi *et al.* (2023: *Journal of Hydrology: Regional Studies*) evaluate the historical drought in the Lower Mekong River Basin during 2015–16. The spatiotemporal dynamics of soil moisture were examined in different ranges of catchment areas, using lagged correlations between hydrological variables and precipitation and streamflow indices. In smaller watersheds, hydrological drought was closely defined with SMAP soil moisture downscaled to 1 km, providing a more easily accessible alternative to ground runoff data-based index. By leveraging satellite-based observations across a range of spatial scales, with more focus on smaller scales than previous studies, this study highlights the utility of Earth observations in informing water resources and land management decisions at the regional scale.

Hazards

The Lower Mekong region is one of the most landslide-prone areas of the world, but despite the need for dynamic characterization of landslide hazard zones within the region, it is largely understudied. Leveraging an open-source data-driven global Landslide Hazard Assessment for Situational Awareness model framework, Biswas *et al.* (2022: *Frontiers in Earth Science*) develop a region-specific dynamic landslide hazard system leveraging satellite-based Earth observation data to assess landslide hazards across the lower Mekong region. An extreme gradient boosting decision tree model was trained for the monsoon period of 2015–2019 and the model was evaluated with independent inventory information for the 2020 monsoon period with the model performance demonstrating considerable skill. The goal of the work, which was developed in collaboration with the Asian Disaster Preparedness Center as part of the NASA SERVIR Program's Mekong hub, is to develop a suite of tools and services on accessible open-source platforms that support and enable stakeholder communities to better assess landslide hazard and exposure at local to regional scales for decision making and planning.

Rainfall-triggered landslides can result in devastating loss of life and property damage and are a growing concern from a local to global scale. Dandridge *et al.* (2023: *Sustainability*) evaluate global patterns in landslide reporting from events in NASA's global landslide catalog (GLC) which compiles a record of rainfall-triggered landslide events from media reports, academic articles, and existing databases at global scale over a decade. The most notable landslide hotspots are in the Pacific Northwest of North America, High Mountain Asia, and the Philippines. Additionally, the relationship between country GDP and income status with landslide occurrence was determined to have a positive correlation between economic status and landslide reporting.

In August, 2021, a strong earthquake struck Haiti triggering thousands of landslides, and only three days later, Tropical Storm Grace crossed shallow waters offshore of southern Haiti triggering more landslides worsening the situation. These events provided a unique opportunity to test different automated landslide detection methods that utilized both SAR and optical data in a rapid response scenario where rapid situational awareness was critical. Amatya *et al.* (2023: *Natural Hazards*) summarize the landslide rapid response products released by several organizations, detection methods, quantify accuracy and provide guidelines on how some of the shortcomings encountered in this effort might be addressed in the future. A manually mapped polygon-based landslide inventory covering the entire affected area was also created and released through this effort.

Another global hazard that is being studied in great detail is atmospheric rivers. Atmospheric rivers (ARs) are meteorological systems that deliver enormous quantities of water poleward from the tropics. They are the major sources of snowpack, extreme precipitation and floods in the semi-arid western United States. In recent years, greater attention has been played to ARs globally, with an AR scale of intensity. In the current study, Guan *et al.* (2023: *JGR-Atmospheres*) explore 40 years of ARs in detail including the global spatial distributions, year-to-year variations and life cycle characteristics of ARs classified by intensity. Their database provides a new resource for better understanding AR characteristics, impacts, and life cycle evolution across different regions around the globe.

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.

The following paper provides a new spectral database for applications in remote sensing of water quality. Remote sensing of water quality is important not just for public health management, but also coastal ecology, chlorophyll-a and studies of climate change. Large and globally representative in situ datasets are essential for the development and validation of bio-optical algorithms to support large-scale monitoring using satellite Earth observation technologies. For coastal and inland water basins, Lehmann *et al.* (2023: *Scientific Data*) provide the major achievement of a globally representative UV-VIS-SWIR reflectance hyperspectral database called the "GLObal Reflectance community dataset for Imaging and optical sensing of Aquatic environments (GLORIA)". This is now the standard for state of knowledge of in situ coastal and inland aquatic optical diversity. The GLORIA dataset will contribute to future improvements in algorithms that retrieve water quality in coastal and inland waters for Earth-observing satellites such as Landsat-8 and Sentinel-2. The data are free and open and accessible at PANGAEA.

Wetlands

While wetlands have long been drained for human use, thereby strongly affecting greenhouse gas fluxes, flood control, nutrient cycling and biodiversity, the global extent of natural wetland loss remains remarkably uncertain. Fluet-Chouinard *et al.* (2023: *Nature*) reconstruct the spatial distribution and timing of wetland loss between 1700 and 2020, by combining national and subnational records of drainage and conversion with land-use maps and simulated wetland extents. They found that 3.4 million km^2 (confidence interval 2.9–3.8) of inland wetlands have been lost since 1700, primarily for conversion to croplands. This lower than previously suggested net loss of 21% of global wetland area since 1700 was primarily for conversion to croplands, concentrated in Europe, the United States and China, and rapidly expanded during the mid-twentieth century. The importance of this study is that it provides a historical baseline to guide assessment of wetland loss impact on Earth system processes, conservation planning to protect remaining wetlands and prioritization of sites for wetland restoration.

Roughly half of all wetlands are found north of 45 degrees latitude, and they are important for the water cycle (ecology and societal water use), greenhouse gas emissions and climate change. For these reasons, it is critical to map transient wetland inundation (flooding) in the Boreal region. Huang *et al.* (2022: *GIScience & Remote Sensing*) developed a two-step modified decision-tree algorithm implemented in Google Earth Engine using Sentinel-1 C-band SAR and Sentinel-2 Multispectral Instrument (MSI) time-series data as inputs to track boreal wetland inundation and its spatiotemporal patterns in boreal areas of Alaska and Alberta. Temporal variability, frequency, and maximum extents of transient wetland inundation are quantified. They validated inundation estimates with in-situ field measurements from the NASA Arctic-Boreal Vulnerability Experiment (ABoVE), and a multi-temporal Landsat-derived surface water map. They conclude that time series of Sentinel-1 C-band SAR backscatter, screened with Sentinel-2 MSI optical imagery and validated by field measurements, offer a valuable tool for tracking transient boreal wetland inundation.

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 take observations of 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 understand the weather producing 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**, WAD supports calibration and product generation for weather and atmospheric dynamics related parameters (e.g., 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. In order to maintain data continuity, three of the major long-term environmental data sets developed for the research communities highlighted in this report are the Climate Hyperspectral Infrared Radiance Product (CHIRP), the Integrated Multi-SatellitE Retrievals for Global Precipitation Measurement (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 CHIRP and CLIMCAPS are long-term atmospheric state data sets. As part of WAD's support of the Open Source Science Initiative (OSSI), both CHIRP and CLIMCAPS are made freely available in the AWS cloud.

WAD funds work that support the 2017 Decadal Survey especially those associated with Atmosphere Observing System (AOS) especially in measurement and characterization of convections, concept development of Planetary Boundary Layer (PBL), and field experiment and concept validation of 3-D Winds. Significant progress measured in publications are reported in this reporting period.

In this time period, WAD ran three field campaigns: IMPACTS, Airborne Lightning Observatory for Fly's Eye GLM Simulator (FEGS) and Terrestrial Gamma-ray Flashes (ALOFT), and CPEX-CV. While IMPACTS is an EV3 mission, ALOFT and CPEX-CV are directly funded by WAD, focusing, respectively, on lightning in the gaulf of Mexico and atmospheric winds and convective processes in the eastern equatorial Atlantic ocean. These activities are reported at the end of this section.

Characterizing the Behavior of the Atmosphere:

Hyperspectral Infrared Radiance Climate Records: CrIS is the follow-on hyperspectral infrared sounder to AIRS, there are currently three CrIS instruments operating in orbit. Taylor et al. (2023) present a model for the polarization-induced calibration bias and the associated correction for the CrIS instruments, along with details of the model parameter determination, and the impact of the correction on the calibrated radiances for a range of scene temperatures and types. This work is based on measurements from in-orbit maneuvers performed after each launch. A wide variety of atmospheric and climate research using AIRS and CrIS depend upon high radiometric calibration, and especially inter-instrument calibration differences. Loveless et al (2023) provided a in-depth analysis of the calibration differences among the three major operating infrared hyperspectral satellite sounders: CrIS, AIRS, and EUMETSAT's IASI sensor, giving users concrete corrections in order to improve geophysical products derived using multi-satellite datasets.

Multi-platform, Multi-instrument Long-term Sounding Record: The PI of the Community Long-term Infrared Microwave Coupled Atmospheric Product System (CLIMCAPS) has worked with the Sounder SIPS to redesign the Level 2 and Level 3 product files in response to user feedback and NASA's call for open-source science. The CLIMCAPS team participated in the 2023 NASA Openscapes Champions Lesson Series April - June, 2023 (doi.org/10.5281/zenodo.7407246). They concluded this series with the launch of a community GitHub page (https://github.com/CLIMCAPS-tools) for open-source sounder science tools. The CLIMCAPS team published two papers describing the data record from infrared and microwave instrument pairs on Aqua, Suomi-NPP and JPSS-1 and evaluation of its quality (Smith & Barnet 2023a, 2023b). CLIMCAPS products have been used to demonstrate the derivation of 3D winds from satellite H2O profiles (Ouyed et al., 2023). Barnet et al. (2023) used the CLIMCAPS framework to evaluate pros and cons of sounding of temperature and water vapor using only the CrIS shortwave region (2155–2550 cm^{-1}) compared to the full spectral range, with a view to design of future instruments. The CLIMCAPS framework also includes the capability to maintain the NUCAPS near-real-time processing capability. This capability has been applied to AIRS measurements in support of severe weather forecasting (Berndt et al., 2023).

Characterizing Atmosphere-surface Boundary Condition:

Cyclone Global Navigation Satellite System (CYGNSS) for Measuring Ocean Surface Winds: CYGNSS produces several different ocean surface wind speed products. The product most commonly used for global scientific investigations is its Science Data Record Fully Developed Seas 10 meter–referenced neutral stability-equivalent wind speed (FDS). The current version (v3.1) was released in 2021 and an updated characterization and assessment of its performance is presented in Asharaf et al. (2022). A new ocean surface wind speed product was also recently released – the Level 3 Storm Centric Gridded (L3 SCG) wind speed (Mayers et al., 2023). The L3 SCG product aggregates wind speed measurements made by the entire CYGNSS constellation over 6-hourly windows. Winds are regridded in a storm-centric coordinate system to account for storm motion within the time window and the results significantly improve the resolution of storm structure. The consistency of spatial coverage makes L3 SCG data a valuable product for historical storm reanalysis. Latent and sensible heat fluxes (LHF and SHF) at the ocean surface are functions of wind speed as well as air–sea humidity and temperature differences. The CYGNSS FDS wind speed product, combined with reanalysis data for the thermodynamic variables, is used to produce LHF and SHF data products. A current version (v2.0) of the CYGNSS Ocean Surface Heat Flux product was released in 2022 and is being used by a number of ongoing investigations into Madden–Julian Oscillation (MJO) convection and extratropical cyclone (ETC) genesis and development. Surface fluxes are found to strongly influence the propagation of organized convective systems, affecting both local and global climate (Hudson and Maloney, 2023; Natoli and Maloney, 2023; Riley-Dellaripa et al., 2023). Specifically, analysis based on CYGNSS observations indicates that the ability of the MJO to propagate across the Maritime Continent depends in part on the presence of strong surface fluxes. In addition, the magnitude and distribution of ocean surface heat fluxes influence the distance to which convection that develops over land will propagate out over near ocean waters. ETCs are primarily located outside of the range of CYGNSS observations. However, they often form in the subtropics and lower middle latitudes where there is good coverage. Leveraging the unique sampling properties of the CYGNSS observations, science team members have investigated the relationship between ocean surface fluxes and storm properties. In a study of more than 4000 individual storms, research using CYGNSS data uncovered systematic relationships among fluxes west of the cold front as well as storm cloud properties and the intensity and distribution of precipitation (Naud et al., 2023).

Characterizing Convection and Precipitation:

Extending the Long-term Record of Thunderstorm Precipitation Features beyond the Tropics: A new combined dataset of the Global Precipitation Measurement (GPM) and Geostationary Lightning Mapper (GLM) observations was developed by Heuscher et al. (2022) to better understand relationships between lightning and precipitation properties over a larger domain than that of the historically sampled global tropics. This study demonstrated some unique aspects of extratropical thunderstorms compared to tropical thunderstorms. It was found that the synoptic-scale environment exhibits more control on early-stage deep convection outside the tropics when compared with more intense/mature storms. In addition, thunderstorms outside the tropics are characterized by stronger convective growth and less variation in ice-phase depth than in the tropics.

A Nowcasting Approach for Low Earth Orbit Hyperspectral Infrared Soundings within the Convective Environment: Through a partnership with JPL and the NOAA JPSS Proving Ground novel methodologies were developed to expand the temporal resolution of low earth orbit hyperspectral infrared soundings (Kahn et al. 2023). Trajectory modeling was leveraged to fill the time gaps between satellite overpasses to create hourly satellite sounding products to support convective weather forecasting applications. JPL developed a methodology leveraging trajectory modeling and Aqua AIRS retrievals to traces environmental information backward in time from storm reports. This method was adapted to use NOAA NUCAPS retrievals and forward trajectory modeling to provide high-temporal resolution soundings to NOAA NWS for convective monitoring. The experimental NUCAPS-Forecast system was run in real-time in the spring of 2019, 2021, and 2023, tested with forecasters at the NOAA Hazardous Weather Testbed, and operations-to-research feedback led to science improvements in the methodology during 2022. Kahn et al. (2023) analyzed the tendencies of derived convective available potential energy (CAPE), and convective inhibition (CIN) are evaluated against gridded, hourly accumulated rainfall obtained from the Multi-Radar Multi-Sensor (MRMS) observations for 24 hand-selected cases over the contiguous United States. Areas with forecast increases in CAPE (reduced CIN) are shown to be associated with areas of precipitation. The increases in CAPE and decreases in CIN are largest for areas that have the heaviest precipitation and are statistically significant compared to areas without precipitation. These results imply that adiabatic parcel advection of LEO satellite sounding snapshots forward in time are capable of identifying convective initiation over an expanded temporal scale compared to soundings used only during the LEO satellite overpass time. The set of 24 case studies analyzed in Kahn et al. (2023) and demonstrate NUCAPS-Forecast skill in predicting the location of convection and heavier precipitation.

Convective Organization and 3D Structure of Tropical Cloud Systems Deduced from Synergistic A-Train Observations and Machine Learning: Stubenrauch et al. (2023) are building a three-dimensional description of upper tropospheric cloud systems to better understand the relationship between convection and cirrus anvils. They used cloud data from AIRS and the Infrared Atmospheric Sounding Interferometer (IASI), and atmospheric and surface properties from the meteorological reanalyses ERA-Interim. They use neural network models trained on collocated radar–lidar data from the A-Train to include cloud top height, cloud vertical extent and cloud layering, along with rain intensity classification to describe the cloud systems. They find that deeper convection leads to larger heavy rain areas and larger estimated detrainment, with a slightly smaller observed emissivity for thick anvil. These data cloud can be used for a process-oriented evaluation of convective precipitation parameterizations in climate models, and to investigate tropical convective organization metrics.

Testing Convective Quasi-Equilibrium Theory: Li et al. (2023) use tropical atmospheric temperature and moisture profiles measured by AIRS to test convective quasi-equilibrium theory. In this theory, tropical tropospheric temperature perturbations are expected to follow moist adiabatic vertical profiles. The shape of these profiles is constrained by convective overturning. Deep convection mostly occurs when the lower troposphere is close to saturation, and their calculations indicate that tropospheric temperature perturbations tend to be consistent with the quasi-equilibrium assumption where the environment is favorable to deep convection, or with a high level of neutral buoyancy (LNB). Profiles with a low LNB, as characterized by a drier troposphere beneath 600 hPa, are less consistent with the convective quasi-equilibrium theory.

Assessment of Satellite Measurements of Upper Tropospheric Humidity: Accurate knowledge of water vapor is essential for quantifying its response to and feedback on climate change. As part of the Stratosphere-troposphere Processes And their Role in Climate (SPARC) Water Vapor Assessment activity, Read et al. (2022) inter-compared twenty-one satellite datasets of upper tropospheric humidity and compared with coincident balloon sonde measurements. Upper tropospheric humidity is a challenging measurement due to large concentration variations, sharp gradient changes, and cloudiness. While the satellite fields show similar features in maps and time series, quantitatively they can differ by a factor of 2 in concentration, but agreement between the NASA AIRS and MLS instruments is within 10% except at concentration extremes.

Surface-to-space Atmospheric Waves from Hunga Tonga-Hunga Ha'apai Eruption: The January 2022 Hunga Tonga–Hunga Ha'apai eruption was one of the most explosive modern volcanic events, producing a plume that reached more than 50 km height. The event triggered atmospheric Lamb waves that propagated around the world multiple times at the speed of sound, and gravity waves of unprecedented magnitude and extent travelling at nearly the speed of sound. Wright et al. (2022) used a comprehensive set of satellite and ground-based observations to quantify the wave response. Latent heat release from the plume remained the most significant individual gravity wave source worldwide for more than 12 hours, producing circular gravity wavefronts across the Pacific basin in detectable in satellite observations by AIRS and other infrared sounders, and in ground-based sensors.

Improved Hydrologic Analysis: The intensity–duration–frequency (IDF) curve is the main input for hydrologic analysis or hydraulic design for flood control. However, the regions with higher flood risks due to extreme precipitation are often deficient in precipitation gauges. Lau and Behrangi (2022) presented a detailed evaluation of IDF curves computed using V06 IMERG Final half-hourly precipitation, fitted with three widely used CDFs, as well as IDF curves using areal average gridded precipitation constructed from two dense gauges networks over (1) the WegenerNET Feldbach region in the Alpine forelands of Austria and (2) the gauge network of the Walnut Gulch Experimental Watershed, in a semiarid region of the United States. The frequency analysis for return periods between 2 and 100 years was based on half-hourly rainfall at the native IMERG spatial resolution, 0.1°×0.1° lat/lon. The order in which the gridded gauge-based precipitation average is performed within a gridbox was evaluated by computing the average before (AB-AMS) and after (AA-AMS) obtaining the Annual Maximum Series (AMS). IMERG AMS agreed better with AB-AMS than AA-AMS for the two study regions, and the Gumbel distribution resulted in better agreement between IMERG and the gauge data.

New Rainfall Error and Autocorrelation Model: Hartke et al. (2023) evaluated a new Space-Time Rainfall Error and Autocorrelation Model (STREAM), which stochastically generates possible true precipitation fields, as input to the Hillslope Link Model to generate ensemble streamflow estimates. Unlike previous error models, STREAM represents the nonstationary and anisotropic autocorrelation structure of satellite precipitation error and does not use any ground reference to do so. They compared ensemble streamflow predictions with streamflow generated using satellite precipitation fields as well as a radar-gauge precipitation dataset during peak flow events. Their results demonstrated that this approach effectively characterizes the uncertainty in streamflow estimates and reduces the error of predicted streamflow nearly to the level obtained using ground-reference forcing data across a range of basin sizes.

IMERG Precipitation Product Skill in Arid Conditions: Precipitation products tend to have large errors in semi-arid regions such as the Southwest United States. This area is also interesting due to its monsoonal precipitation pattern, in which roughly 50% of the region's precipitation falls during the months of June–September. Ehsani et al. (2022) evaluated precipitation products over Arizona and New Mexico for the monsoon seasons of the 2002–2021 period, emphasizing the extreme years of 2020 and 2021. Results indicated that all satellite products tend to capture interannual variations of precipitation rate but struggled to capture high-intensity events. IMERG Final had better performance than other products and the best detection capacity on rainy days. ERA5-Land performed well in capturing the average monsoon precipitation rate, but showed limited skill in the detection of trace, light, and extreme precipitation events. IMERG Late and PDIR-Now had difficulty detecting light precipitation events and overestimated extreme events.

Evaluating Storm Events with Satellite and Surface Radar Precipitation: Precipitation occurs in the form of discrete "events" whose characteristics (duration, depth, peak intensity, start/end time) significantly influence the hydrologic response of stream basins. Li et al. (2023) evaluated the precipitation event performance of the IMERG product using GV-MRMS in the Continental United States (CONUS) at the native IMERG resolution (0.1◦×0.1◦, 0.5 h). They showed that IMERG generally overestimated the event duration but underestimated the mean event precipitation intensity in the summer, while the opposite was true for winter. They attributed this discrepancy to the under-representation of short-duration intense events in the summer and long-duration moderate events in the winter in IMERG. About 50% of the reference events were properly detected by IMERG. However, nearly 40% of the missed or false events result from temporal mismatching of less than 3 h between the retrieved and the reference event. The remaining 60% comes from IMERG not detecting an actual event or reporting a nonexistent event. When IMERG successfully detects an event, the average temporal overlap with the reference event is about 70% of its total duration, which arises because IMERG events tend to start, peak, and end earlier than GV-MRMS events, with national mean shifts of −26 min, −17 min, and −7 min, respectively. About 20% of all starting times are correctly reproduced by IMERG, and this applies to the peak and end times.

<u>Fine-scale Error Model for Estimating IMERG Uncertainty:</u> Li et al. (2023) used a GPM combined radar-radiometer product as an alternative to ground-based observations to develop an estimator for IMERG uncertainty around the globe. The 2BCMB product trained error models based on censored shifted gamma distribution (CSGD; a mixed discrete-continuous probability distribution). Uncertainty estimates from these models were compared against alternative error models trained on GV-MRMS. Using information from NASA's Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2) reanalysis, they demonstrated how IMERG uncertainty estimates can be further constrained using additional precipitation-related predictors.

<u>Oceanic Validation of IMERG:</u> Wang et al. (2022) validated the Integrated Multi-satellitE Retrievals for GPM (IMERG) Versions V05B and V06B precipitation products against ground-based observations from the Kwajalein Polarimetric S-band Weather Radar (KPOL) deployed at Kwajalein Atoll in the central Pacific Ocean at their native 0.1°, 30 min resolution from 2014 to 2018. They showed that both IMERG V05B and V06B underestimated, although IMERG V06B was improved. Tracing the IMERG performance back to individual sensors and morphing-based algorithms, the authors show that the overall underestimation in V05B is mainly driven by the negative relative biases in "morphed" values that are largely corrected in V06B. Passive microwave (PMW) imagers perform generally better than PMW sounders. Among imagers, the GPM Microwave Imager (GMI) and Advanced Microwave Scanning Radiometer Version 2 (AMSR2) were the best, followed by Special Sensor Microwave Imager/Sounder (SSMIS). Among sounders, the Microwave Humidity Sounder (MHS) was the best, followed by Advanced Technology Microwave Sounder (ATMS) and the Sounder for Atmospheric Profiling of Humidity in the Intertropics by Radiometry (SAPHIR) for V06B.

<u>Spectral Error Model for Neighboring Space-Time Dynamics of Precipitation:</u> Error models for satellite precipitation products typically compute the uncertainty as a function of precipitation intensity alone, and only at one specific spatio-temporal scale. Guilloteau et al. (2023) developed a spectral error model that accounts for the neighboring space–time dynamics of precipitation as part of the uncertainty quantification. Systematic distortions

of the precipitation signal and random errors are characterized in the Fourier domain and then represented as a deterministic space–time linear filtering term. The random errors are represented as nonstationary additive noise. The spectral error model is applied to the IMERG precipitation product, and its parameters are estimated empirically using the GV-MRMS as reference over the eastern United States. While traditional error models attribute most of the error variance to random errors, the authors found that the systematic filtering term explains 48% of the error variance at the native resolution of IMERG. They conclude that, at high resolution, the error cannot be represented as a purely random additive or multiplicative term, and that precipitation estimates from different sources do not automatically have statistically independent errors.

Uncertainty in Warm Rain Retrievals: Among the many sources of uncertainty in satellite precipitation retrievals of warm rain, Shulte et al. (2022) focused on spatial heterogeneity and surface clutter, using a cloud-resolving model of warm, shallow clouds to simulate satellite observations from three theoretical satellite architectures—one similar to the GPM Core Observatory, one similar to CloudSat, and one similar to the planned Atmosphere Observing System (AOS). They retrieved rain rates using a common optimal estimation framework and found that retrieval biases due to nonuniform beamfilling are very large, with retrieved rain rates negatively (low) biased by as much as 40%–50% (depending on satellite architecture) at 5 km horizontal resolution. Surface clutter also acted to negatively bias retrieved rain rates. Combining all sources of uncertainty, the theoretical AOS satellite was found to outperform CloudSat in rain rate, with a bias of −19% as compared with −28%, a reduced spread of retrieval errors, and an additional 17.5% of cases falling within desired uncertainty limits.

Identifying Regions of High Precipitation Predictability at Seasonal Timescales From Limited Time Series Observations: Mamalakis et al. (2022) introduced a generalized probabilistic framework for precipitation retrieval uncertainties that accounts for the large number of potential drivers, varying antecedent conditions, and small sample size of high-quality observations available at seasonal timescales, and assessed predictability. Focusing on prediction of winter (November-March) precipitation across the contiguous United States, using sea surface temperature-derived indices (averaged for August-October) as predictors, the authors identify "predictability hotspots," defined as regions where precipitation is inherently more predictable. Their framework estimates the entire predictive distribution of precipitation using copulas and quantifies prediction uncertainties, based on principal component analysis for dimensionality reduction and a cross validation technique to avoid overfitting. The authors evaluated how predictability changes across different quantiles of the precipitation distribution (dry, normal, wet amounts) using a multi-category 3×3 contingency table and showed that well-defined predictability hotspots occur in the Southwest and Southeast. Moreover, extreme dry and wet conditions are shown to be relatively more predictable compared to normal conditions.

Long-term Oceanic Ground Validation: Petty and Tran (2023) assessed trends in precipitation occurrence over the global oceans based on ship present-weather reports from 1950 to 2019, a notably longer record than any other available over the ocean. Annual reported precipitation frequency showed statistically significant positive trends of up to ∼15% per decade throughout most ocean areas equatorward of 45°. However, latitudes poleward of 45° are dominated by negative trends, some areas of which meet the 95%

confidence threshold. Nine smaller regions were subjectively selected for further investigation, revealing that the observed trends, both positive and negative, are often but not always nearly linear, with the amplitude of interannual fluctuations usually being much larger than that expected from random sampling error alone. The annual time series revealed that four comparatively dry areas are associated with the largest overall positive trends, ranging from 8.3% to 12.8% (relative) per decade. Trends were also computed separately for each season, revealing remarkable overall consistency across seasons.

D3R Instrument Overview: Haonan et al. (2022) reported on GV results observed as part of the International Collaborative Experiment during the PyeongChang Olympics and Paralympic winter games (ICE-POP) 2018, which took place in the PyeongChang region of South Korea. The NASA dual-frequency, dual-polarization, Doppler radar (D3R) was deployed for more than four months and was able to capture many interesting snowfall events along with a few rain events. The authors discussed the deployment and performance of the D3R during the campaign, and then the snowfall events captured by the D3R are discussed in detail to interpret the microphysics from a radar's perspective and in comparison with other instruments, such as disdrometers and the MxPOL X-band radar, which matched within a couple of dB. The authors computed the reflectivity–snowfall rate relationship for the Ku band, and the estimated snow accumulation is in good agreement with a precipitation gauge that was deployed near the radar.

PIP Instrument Overview: Tokay et al. (2022) evaluated the performance of the Precipitation Imaging Package (PIP), which estimates the snow water equivalent (SWE), using a comparative study with the collocated NOAA/NWS snow stake field measurements. The PIP, a vertically pointing radar, a weighing bucket gauge, and a laser-optical disdrometer were deployed at the NWS Marquette, Michigan, office for a joint long-term field study. The site was also equipped with a weather station. During the 2017/18 winter, the PIP functioned nearly uninterrupted at frigid temperatures, accumulating 2345.8 mm of geometric snow depth over a total of 499 h. This long record consisted of 30 events, and the authors showed that PIP-retrieved and snow stake field-measured SWE differed less than 15% in every event. Considering two of the major events with the longest duration and the highest accumulation, the particle mass with a given diameter was much lower during a shallow, colder, uniform lake-effect event than in the deep, less cold, and variable synoptic event.

IMERG Performance in Relation to Gauge Network Density: Hartke et al. (2022) compared the performance of interpolated gauge estimates and satellite precipitation data as a function of gauge density to identify the gauge density at which satellite precipitation data and interpolated estimates have similar accuracy using a Monte Carlo interpolation scheme at locations across the continental U.S. and Brazil. They hypothesized that the error in interpolated precipitation estimates increases drastically at low rain gauge densities and at high distances to the nearest gauge, and then showed that IMERG has comparable performance in precipitation detection to interpolated gauge data at very low gauge densities (i.e., less than 2 gauges/10,000 km2) and that IMERG often outperforms interpolated data when the distance to the nearest gauge used during interpolation is greater than 80–100 km. However, they reported variability in this performance 'break point' and the geographical variables of elevation, distance to coast, and annual precipitation.

DPR as a Standard Comparison for WSR-88D: Li et al. (2022) provided the first nationwide comprehensive comparisons at 136 WSR-88D radar sites from 2014 to 2020 between the NOAA ground-based radars – WSR-88D network – and the NASA-JAXA space-borne radar – the GPM/DPR. They found systematic differences in reflectivity, with WSR-88D on average 2.4 dB smaller than the DPR (Version 06). The authors found that the discrepancies arise from different calibration standards, signal attenuation correction, and differences in the ground and space-borne scattering volumes. The recently updated DPR Version 07 product improves rain detection and attenuation corrections, effectively reducing the overall average WSR-88D–DPR reflectivity differences to 1.0 dB.

GV Results from the WFF Precipitation Supersite: The Wallops Precipitation Research Facility (WPRF) at NASA GSFC, Wallops Island, Virginia, provides a semipermanent supersite for the GPM Ground Validation (GV) program, hosting research-quality precipitation instruments that include NASA’s S-band dual-polarimetric radar (NPOL), a network of profiling radars, disdrometers, and rain gauges. Pabla et al. (2022) use these data to investigate the statistical agreement of the GPM Core Observatory Dual-Frequency Precipitation Radar (DPR), combined DPR–GPM Microwave Imager (GMI), and GMI level II precipitation retrievals compared to WPRF ground observations from a 6-yr collection of satellite overpasses. Given that instantaneous satellite measurements are observed above ground level, this study investigates the possibility of a time lag between satellite and surface mass-weighted mean diameter (Dm), reflectivity (Z), and precipitation rate (R) observations. The authors report apparent time lags that vary up to 30 min after overpass time but are not consistent between cases. In addition, GPM Core Observatory Dm retrievals are within level I mission science requirements as compared to WPRF ground observations. Results also indicate GPM algorithms overestimate light rain (<1.0 mm h^{-1}). The authors analyze two very different stratiform rain vertical profiles that show differing results when compared to ground reference data. A key finding of this study indicates that DPR/GMI combined algorithms outperform single-sensor DPR algorithms.

Machine Learning on the Planetary Boundary Layer from Thermal and Microwave Sounders: Milstein et al. (2023) present a new deep neural network approach to improve representation of key features of the structure of the planetary boundary layer (PBL) over land (such as temperature inversions associated with convective activity). This project was funded to support the 2017 Decadal Survey and it demonstrated the use of AI/ML to extract information from hyperspectral AIRS measurements for a new decadal survey requirement.

The Role of Free Tropospheric Moisture in the Development of Heavy Precipitation: A recent study has utilized the passive MW observations from the Advanced Technology Microwave Sounder (ATMS) to estimate the precipitation profile structure associated with near-coincident COSMIC-2 moisture and temperature observations (Turk et al., 2022). The path-integrated nature of the RO naturally averages moisture to a scale that can be replicated with current climate model resolutions. These joint data enable the computation of convective transition statistics with spatial/temporally aligned temperature, moisture and precipitation observations. Differences between the convective transition relationships between various Coupled Model Intercomparison Project (CMIP6) climate models and COSMIC-2 observations were reported, when conditioned upon quantities that are relevant to the impact of lateral entrainment. Inter-model spread in statistics of the vertical thermodynamic structures associated with convective instability appears to be linked to representations of the entrainment process.

CYGNSS and Geostationary Environmental Monitoring and Characterization

Freeze/Thaw Detection: Changes in CYGNSS observed reflectivity over land are used to detect transitions in the Freeze/Thaw (F/T) state of the surfaces. This capability has been applied to observations over an area in South America covering the Andes Mountains and the Argentinian Pampas. The results show that CYGNSS is responsive to changes in surface permittivity, which is then leveraged to detect transitions of freeze-thaw surface state (Carreno-Luengo and Ruf, 2022a,b). The CYGNSS observations have enhanced spatiotemporal sampling as compared to previous methods. This F/T detection capability can be extended to current and upcoming polar-orbiting CYGNSS follow on missions in orbit and in development by private industry and ESA, to support the monitoring of arctic permafrost active layer dynamics.

Inland Water Inundation Mapping: CYGNSS sensitivity to inland water bodies, and its ability to finely resolve small water features in day/night, clear/cloudy, and bare/vegetated surface conditions is being exploited by a number of investigations. One recent study demonstrates that inundation maps have greater surface water extent than retrievals produced with data from other remote sensing instruments, including optical (MODIS), infrared (VIIRS) and microwave (the SWAMPS product and data from Sentinel-1) (Downs et al., 2023). These results have important implications for quantifying seasonal inundation dynamics in the tropics and also for modeling of methane production (Gerlein-Safdi et al., 2021).

Field Campaign for 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 and midwestern 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. IMPACTS collected data from over 35 winter storms that occurred in winters 2020, 2022, and 2023. During the last IMPACTS deployment in 2023, the project sampled a wide variety of types of winter storms with the highest number of coordinated flights between the high altitude and in situ aircraft compared to earlier deployments. An overview article (McMurdie et al., 2022a) appeared in the flagship journal of the American Meteorological Society that describes the IMPACTS project and highlights preliminary results from the 2020 deployment, and the 2022 deployment was highlighted in McMurdie et al. (2022b). Several publications appeared this past year using IMPACTS data. Dunnavan et al. (2023) compared retrievals of microphysical properties using radars of difference frequencies, platforms and methodologies. Their study was one of the first to compare mass-weighted mean diameter of cloud and precipitation particle retrievals from both nadir-pointing airborne multi-frequency radars and ground-based polarimetric range-height indicator radar scans along the same airborne flight track. Varcie et al. (2023) and Colle et al. (2023) focused on the 7 February 2020 event sampled during the first year of IMPACTS. Varcie et al. (2023) compared the microphysical properties in the convective and stratiform regions of the storm at multiple altitudes. Colle et al. (2023) simulated precipitation distribution and microphysical properties and compared the model simulations to in situ measurements from IMPACTS measurements. They found more significant differences in modeled precipitation distribution due to differences in initializations than due to differences in microphysics schemes. Heymsfield et al. (2023) used coincident radar data with Doppler radar measurements at four frequencies together with in situ microphysical measurements made during coordinated flight legs. They derived relationships between microphysical properties, such as the measured ice water content and properties of the particle size distributions, and the measured reflectivity factor obtained from airborne radars at the various wavelengths. These relationships can be used in studies to characterize the properties of wintertime snow clouds. There are a total of 17 published articles highlighting IMPACTS results that are advancing our understanding of snowfall and precipitation processes in winter extratropical cyclones. The team plans to continue their studies of precipitation processes, remote sensing, and modeling of snowfall within winter storms.

Field Campaign Makes New Discoveries about Gamma-ray Radiation from Thunderstorms:

The Airborne Lightning Observatory for Fly's Eye GLM Simulator (FEGS) and TGFs (ALOFT; https://ntrs.nasa.gov/api/citations/20230005812/downloads/ALOFT_Overview_v2.pdf): ALOFT took place during 1-30 July 2023 out of Tampa, Florida using the NASA ER-2, made startling discoveries about the abundance of gamma-ray glows and TGFs in tropical thunderstorms. Originally thought to be up to 10,000 times rarer than lightning, TGFs instead were detected on most ALOFT science flights, and appear to be related to the presence of low-level, longer-lived gamma-ray emissions known as glows. ALOFT is finding glows to be common in the intensifying-to-mature stages of tropical thunderstorm cells. Observations from ALOFT are thus physically relating the production of high-energy radiation to the lifecycles of tropical thunderstorms. Decision-support tools and datasets produced by the NASA Short-term Prediction Research and Transition Center (SPoRT) played an important role in ALOFT mission science via the NASA Mission Tools Suite (MTS). ALOFT was a collaboration with the University of Bergen, and used multiple lightning and microwave sensors from Marshall and Goddard Space Flight Centers. ALOFT also provided validation data for the International Space Station Lightning Imaging Sensor (ISS LIS) and Geostationary Lightning Mappers (GLMs), and tested multiple new concepts for future spaceborne lightning measurements.

Field Campaign for Remote Sensing of Dynamics, Convection, and Saharan Air in the Tropical North Atlantic:

Convective Processes Experiment – Cabo Verde (CPEX-CV): CPEX-CV (https://www-air.larc.nasa.gov/missions/cpex-cv/index.html) was a NASA field campaign that took place September 1-30, 2022, using the NASA DC-8 out of Sal Island, Cabo Verde. CPEX-CV was a continuation of the NASA CPEX – Aerosols and Winds (CPEX-AW) deployment that took place out of St. Croix, U.S. Virgin Islands in 2021. Now deployed in the data-sparse eastern tropical North Atlantic, CPEX-CV investigated the process-level interactions between atmospheric dynamics, marine boundary layer properties, convection, the dust-laden Saharan Air Layer across various spatiotemporal scales. CPEX-CV utilized the cutting-edge CPEX-AW payload that included active (e.g., High Altitude Lidar Observatory [HALO], Doppler Aerosol WiNd Lidar [DAWN], Airborne Third Generation Precipitation Radar [APR-3]) passive (e.g., High Altitude Monolithic Microwave integrated Circuit [MMIC] Sounding Radiometer [HAMSR]) and *in situ* sensors (e.g. dropsondes), augmented with measurements of aerosol and cloud particle size distributions (e.g., Cloud Aerosol and Precipitation Spectrometer [CAPS], High Ice Water Content [HIWC] instrumentation). Utilizing this instrumentation suite, CPEX-CV performed 13 research flights that totaled over 90 hours and released over 400 dropsondes to measure the evolution of atmospheric dynamics, thermodynamics, composition, and microphysics in numerous environments. These observations included convective lifecycle in the context of easterly waves, including those that would eventually become Hurricanes Ian and Fiona, in situ measurements of Tropical Storm Hermine, and the highest dust optical depth ever measured by the NASA DC-8 in a major Saharan air outbreak. A key to the success of the field deployment included continued collaboration with domestic and international partners. In addition to the U.S. Office of Naval Research, CPEX-CV collaborated with European Space Agency (ESA) partners to perform several underpasses of ESA’s Atmospheric Dynamics Mission-Aeolus wind lidar and coordinated efforts to overpass ESA partner ground-based sites and aircraft. A notable success story of CPEX-CV was the empowerment of early career participants in leadership roles that helped train the next generation of mission scientists, flight planners, and forecasting leads for future NASA field campaigns.

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 the last year to (a) elucidate interactions and impacts of aerosol and clouds upon radiation; (b) better understand the processes that occur in smoke plumes and their effects downstream ; (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, as well as the evolution and impacts of aerosols, in particular smoke particles injected into the upper atmosphere.

A. Aerosols, clouds and radiative forcing

Aerosol properties and processes

The ACFA Radiation Sciences Program (RSP) and associated space-borne missions and sub-orbital projects support a broad range research on aerosols, clouds and the Earth's radiative flux. Here we summarize eleven papers on aerosol properties and processes, aerosol-cloud-radiative interactions and cloud and aerosol radiative forcing.

Bruckert et al. (2023) explored ash aerosol aging and sulfate production following the 2021 La Soufrière (St. Vincent) eruption. Modeled aerosol distribution and composition were compared with data from CALIOP, MISR, and the Barbados Cloud Observatory. The modeled aerosol aging agreed well with satellite observations and showed particle aging occuring faster in the troposphere than in the stratosphere due to the availability of water vapor and OH, but a layer of coated ash appeared at the plume top due to faster oxidation of SO_2 and lofting by aerosol-radiation interaction. This paper gives the first direct comparison of modeled and observed aerosol aging in volcanic eruption plumes.

Secondary organic aerosols (SOA) formed by the oxidation and gas-aerosol partitioning of precursor organic vapors are an important, yet unsettled, source of cloud condensation nuclei (CCN), and thus can affect cloud properties globally and the Earth's radiative balance. **Liu and Matsui (2022)** estimate the impact of SOAs on CCNs by constraining an aerosol-climate model using *in situ* aircraft measurements for number and mass concentrations of aerosols. They find SOAs formed by the oxidation of primary organic vapors from anthropogenic and natural emissions dominate the growth of small particles to CCN in the global remote troposphere. The formation of SOAs exerts larger percentage contributions to CCN in preindustrial atmosphere than in the present day, appreciably altering the magnitude of cloud radiative forcing.

Southern Africa produces a third of global biomass burning emissions, which have a long atmospheric lifetime and influence regional radiation balance and climate. **Che et al. (2022)** investigate the evolution of biomass-burning aerosols during transport from Southern Africa over the southeastern Atlantic. They find initial secondary organic aerosol formation, followed by decreases in organic aerosol via photolysis, with aerosol absorption wavelength dependency decreasing from an increase in particle size and photochemical bleaching of brown carbon. Cloud processing, including aqueous-phase reaction and scavenging, contributes to the oxidation of organic aerosols, while it strongly reduces large diameter particles and single-scattering albedo of biomass burning aerosols. Together, these processes resulted in a marine boundary layer with fewer yet more oxidized and absorbing aerosols.

Li et al. (2023a) used *in situ* measurements and large-eddy simulations (LES) to investigate aerosol effects on micro/macrophysical properties of marine stratocumulus clouds over the western North Atlantic Ocean (WNAO) for two cold-air outbreak cases during the Aerosol Cloud Meteorology Interactions over the Western Atlantic Experiment (ACTIVATE) in 2020. The LES are able to reproduce the vertical profiles of liquid water content (LWC), effective radius r_{eff} and cloud droplet number concentration N_c from fast cloud droplet probe (FCDP) in situ measurements for both cases. They also find that aerosols affect cloud properties (*Nc*, *r*eff, and LWC) via the prescribed bulk hygroscopicity of aerosols and aerosol size distribution characteristics. N_c, r_{eff}, and liquid water path (LWP) are positively correlated to the hygroscopicity and aerosol number concentration (N_a) while cloud fractional cover (CFC) is insensitive to it and to aerosol size distributions. Comparisons of ERA5 and MERRA-2 reanalyses show the former is better than the LES in capturing the time evolution of LWP and total cloud coverage within the study domain.

Aerosol-cloud-radiative interactions

Wall et al. (2022) used CERES and MODIS observations along with MERRA-2 meteorological fields and sulfate–aerosol mass concentrations to quantify relationships between sulfate aerosols and low-level clouds after controlling for meteorology using a cloud-controlling factor analysis. They determined the cloud-mediated radiative forcing from anthropogenic sulfate aerosols is -1.11 ± 0:43 Wm-2 over the global ocean (95% confidence). This implies the equilibrium climate sensitivity (ECS) is likely between 2.9 and 4.5 K (66% confidence). The results indicate aerosol forcing is less uncertain and ECS is probably larger than the ranges proposed by recent climate assessments.

CloudSat measurements reveal tropical cyclones that intensify versus those that weaken contain greater amounts of ice in the vicinity of the storm center. The observations also show how this ice results in larger radiation heating near the center of the intensifying tropical cyclones. This heating drives an enhanced thermally direct circulation that further sustains the storm. **Wu et al (2023)** demonstrate how model forecasts of intensity of tropical cyclones improve when the model better reproduces the observed spatial structure of radiative the heating associated with the tropical cyclone.

Cloud and aerosol radiative forcing

During the Arctic night, clouds regulate surface energy budgets through longwave warming alone. During fall, any increase in low-level opaque clouds will increase surface cloud warming and could potentially delay sea ice formation. While an increase in clouds due to fall sea ice loss has been observed, quantifying the surface warming is observationally challenging. **Arouf et al. (2023)** quantify surface cloud warming using spaceborne lidar observations. By instantaneously co-locating surface cloud warming and sea ice observations in regions where sea ice varies, they find October large surface cloud warming values (> 80 W m-2) are much more frequent (~+50%) over open water than over sea ice. Notably, in November large surface cloud warming values (> 80 W m-2) occur more frequently (~+200%) over open water than over sea ice. These results suggest more surface warming caused by low-level opaque clouds in the future as open water persists later into the fall.

Atmospheric aerosols and their impact on cloud properties remain the largest uncertainties in the anthropogenic forcing of the climate system. Based upon satellite data and model simulations, **Gryspeerdt et al. (2023)** found that the diversity of the susceptibility of cloud droplet number to aerosols resides, counterintuitively, mostly in the clean condition, which leads to much of the variation in the radiative forcing from aerosol-cloud interactions in global climate models. As a result, better constraining aerosol behavior in clean conditions is critically needed in order to reduce uncertainty in aerosol forcing in these climate models.

Aerosol forcing uncertainty represents the largest climate forcing uncertainty overall. Its magnitude has remained virtually undiminished over the past 20 years despite considerable advances in understanding most of the key contributing elements. Recent work has produced only modest increases in confidence of the uncertainty estimate itself. In their review, **Kahn et al. (2023)** summarize the contributions toward reducing the uncertainty in the aerosol forcing of climate made by satellite observations and measurements taken within the atmosphere, as well as modeling and data assimilation. They conclude that currently-planned programs supporting (a) advanced, global-scale satellite and surface-based aerosol, cloud, and precursor gas observations, (b) climate modeling, and (c) intensive field campaigns aimed at characterizing the underlying physical and chemical processes involved, are all essential. New efforts also are needed to obtain systematic aircraft *in situ* measurements of aerosol particle and cloud properties, as well as co-variability with meteorology. Finally, they argue for a renewed focus on integrating the unique contributions of satellite observations, suborbital measurements, and modeling, in order to reduce the persistent uncertainty in aerosol climate forcing.

Shaw and Kay (2023) investigated Arctic longwave radiation emergence using climate model large ensembles. Due to seasonally dependent sea ice loss and surface warming, longwave radiation emergence timing varies through the year with fall emergence occurring a decade earlier than spring emergence. The atmosphere and clouds then widen these seasonal differences by delaying emergence more in the spring and winter than in the fall. Overall, these findings demonstrate that attributing changes in Arctic outgoing longwave radiation to human influence requires understanding the seasonality of both forced change and internal climate variability.

Assimilation of hyperspectral infrared sounder observations aboard Earth-observing satellites provide important constraints on atmospheric temperature and moisture and thus are a key component of modern numerical weather prediction. **Marquis et al. (2023)** use collocated observations from the AIRS hyperspectral infrared sounder and the CALIPSO lidar to show a significant number of infrared radiances assimilated into the operational Navy forecast model are contaminated by undetected cirrus clouds, resulting in biased weather forecasts. Several potential mitigations are proposed, involving the incorporation of additional satellite observations into the model assimilation system.

B. Biomass burning, wildfires and smoke processes, chemistry of the remote atmosphere, and health effects of air pollution

Research supported by the ACFA Tropospheric Composition Program (TCP) is focused on the changing composition of the troposphere and the processes that impact air quality, particularly on regional scales. Summarized in this subsection are seven papers on processes in biomass burning, wildfires and the smoke plumes the produce, the chemistry of the remote troposphere and a the health effects of air pollution.

Biomass burning, wildfires and smoke processes

Wildfires emit large amounts of black carbon and light-absorbing organic carbon, but the atmospheric warming from brown carbon remains highly variable and poorly represented in climate models compared with that of the relatively nonreactive black carbon. Given that wildfires are predicted to increase globally in the coming decades, it is increasingly important to quantify these radiative impacts. **Chakrabarty et al. (2023)** present measurements of ensemble-scale and particle-scale shortwave absorption in smoke plumes from wildfires in the western United States and find that a type of dark brown carbon contributes three-quarters of the short visible light absorption and half of the long visible light absorption. This strongly absorbing organic aerosol species is water insoluble, resists daytime photobleaching and increases in absorptivity with night-time atmospheric processing. These findings suggest that parameterizations of brown carbon in climate models need to be revised to improve the estimation of smoke aerosol radiative forcing and associated warming.

Tomsche et al. (2023) report data collected during the 2019 Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) study from smoke plumes emitted from 6 western wildfires, 2 prescribed grassland fires, 1 prescribed forest fire in the South, and 66 small agricultural fires in the Southeast. Smoke plumes contained double to triple digit ppb levels of NH_3. In the wildfire plumes, a significant fraction of NH_3 had already been converted to submicron ammonium particulate (NH_4^+) within a few hours of emission, while substantial amounts of NH_4^+ were detected in freshly emitted smoke from corn and rice field fires. Average NH_3 and NH_x emission factors for wildfires in the Western United States were 1.86±0.75 g kg^{-1} and 2.47±0.80 g kg^{-1} of fuel burned, respectively. Average NH_3 and NH_x emission factors for agricultural fires in the Southeastern United States were 0.89±0.58 and 1.74±0.92 g kg^{-1}, respectively. Their data show no clear inverse correlation between modified combustion efficiency (MCE) and NH_3 emissions. The observed NH_3 emissions were significantly higher than measured in previous laboratory experiments in the FIREX FireLab 2016 study.

Fires emit sufficient sulfur to affect local and regional air quality and climate. **Rickly et al. (2022)** analyze SO_2 emission factors and variability in smoke plumes from US wildfires and agricultural fires, as well as their relationship to sulfate and hydroxymethanesulfonate (HMS) formation. Observed SO_2 emission factors for various fuel types show good agreement with the latest reviews of biomass burning emission factors, producing an emission factor range of 0.47–1.2 g SO_2 kg^{-1} C. These emission factors vary with geographic location in a way that suggests that deposition of coal burning emissions and application of sulfur-containing fertilizers likely play a role in the larger observed values, which are primarily associated with agricultural burning.

Paouyaei et al. (2023) investigated downwind impacts on ozone conccentrations and chemistry from the Williams Flats wildfire (August 3-9, 2019). Assimilating satellite-retrieved nitrogen dioxide (NO_2) and formaldehyde (HCHO) columns improved surface ozone simulations. Simulated ozone compares favorably with aircraft measurements from FIREX-AQ) aircraft measurements in both smoke and non-smoke plumes within the lower troposphere (7.00 ppbv mean absolute error). The study observed higher-than-average concentrations of nitrogen oxides, peroxyacetyl nitrate, nitric acid, and oxygenated volatile organic compounds due to wildfire emissions, which increased ozone concentrations by 3–5 ppbv during the wildfire in near-distance locations and 2–3 ppbv in far-distance locations. During more intense wildfire days, above 120 ppbv carbon monoxide plumes transported over the Rocky Mountains to the east. Ozone regime indicators showed a clear transition area downwind of the wildfire region that exacerbated the formation of ozone downwind. These findings suggest that a joint assimilation of NO_2 column, HCHO column, and AOD can enhance our understanding of wildfire-associated ozone chemistry and dynamics.

The optical and chemical properties of biomass burning (BB) smoke particles greatly affect the impact wildfires have on climate and air quality. **Junghenn Noyes et al. (2022)** have developed and validated unique tools to analyze data from the NASA Earth Observing System's Multi-angle Imaging SpectroRadiometer (MISR) instrument to derive wildfire smoke plume heights, the associated wind vectors, and constraints on particle amount, size, shape, and light-absorption properties. They identify the patterns in retrieved particle properties as related to fire intensity, vegetation fuel type, and meteorological conditions during burning, finding that fires in forests produce the thickest plumes and largest, brightest particles and the opposite for fires in savannas and grasslands. The dominant aging mechanisms and the timescales over which they occur vary systematically between vegetation types. Such information offers important, regional-scale constraints for modelling the impacts of wildfires on air quality.

Chemistry of the remote troposphere

The NASA Atmospheric Tomography (ATom) mission built a photochemical climatology of air parcels based on *in situ* measurements from the NASA DC-8 aircraft along objectively planned profiling transects through the middle of the Pacific and Atlantic oceans. **Guo et al. (2023)** present and analyze a data set of 10 s (2 km) merged and gapfilled observations of the key reactive species driving the chemical budgets of O_3 and CH_4 consisting of over 140,000 distinct air parcels from the four ATom deployments. Six models calculated the O_3 and CH_4 photochemical tendencies from this modeling data stream for ATom 1 and support previous model-only studies that tropospheric chemistry is driven by a fraction of all the air. The model results also show - surprisingly - that much of the heterogeneity in tropospheric chemistry can be captured with current global chemistry models with scales on the order of 100 km. Their comparison of ATom reactivities over the tropical oceans with climatological statistics from six global chemistry models shows generally good agreement with the reactivity rates for O_3 and CH_4. Models distinctly underestimate O_3 production below 2 km relative to the mid-troposphere, and this can be traced to lower NO_x levels than observed.

Health affects of air pollution

Yang et al. (2022) quantify global premature deaths attributable to long-term exposure of ambient $PM_{2.5}$, or $PM_{2.5}$-attributable mortality from dust and pollution sources. For five leading causes of death, the estimated yearly global $PM_{2.5}$-attributable mortality in 2019 was 2.89 (1.38–4.48) million. Mortality counts vary with geopolitical regions substantially, with the highest number of deaths occurring in Asia. 22% of the global all-cause $PM_{2.5}$-attributable deaths are caused by desert dust. Enforcement of the United States air quality standard (AQS) of 15 $\mu g/m^3$ globally would have avoided nearly 40% or 1.2 million premature deaths. This study highlights the importance of distinguishing aerodynamic size from geometric size in accurately assessing the global health burden of $PM_{2.5}$ and particularly for dust. Dust $PM_{2.5}$ from geometric size in model simulations can overestimate the $PM_{2.5}$ level in the dust belt by 40–170%, leading to an overestimate of global all-cause mortality by 1 million or 32%.

C. *Greenhouse gases, the carbon cycle and climate change*

Carbon fluxes and exchanges

With diurnal solar induced chlorophyll fluorescence (SIF) observations from OCO-3 and evapotranspiration from ECOSTRESS on International Space Station, **Zhang et al. (2023)** found a strong depression of dry season afternoon photosynthesis (by 6.7 ± 2.4%) and evapotranspiration (by 6.1 ± 3.1%) in Amazonia forests. They further revealed that photosynthesis positively responds to vapor pressure deficit (VPD) in the morning, but negatively in the afternoon, implying that the regionally depressed afternoon photosynthesis will be compensated by their increases in the morning in future dry seasons. These results shed new light on the complex interplay of climate with carbon and water fluxes in Amazonian forests on diurnal time scale and provide evidence on the emerging environmental constraints of primary productivity that may improve the robustness of future projections.

D. *Stratospheric composition change & ozone depletion*

Summarized in this subsection are seven papers highlighting the important role played by the AGAGE network monitoring compliance with the Montreál Protocol, the causes of changes in stratospheric trace species due to changes in the mass circulation and to the injection of smoke into the stratosphere as seen during the Australian New Year's fires.

AGAGE monitoring of compliance with the Montreál Protocol

Trifluoromethane (HFC-23) is an extremely potent greenhouse gas and is a by-product of the production of the legacy refrigerant and chemical feedstock chlorodifluoromethane (HCFC-22). Park et al. (2023) estimate regional top-down emissions of trifluoromethane (HFC-23) for eastern Asia based on *in situ* measurements at the AGAGE network site at Gosan, South Korea. They show that the HFC-23 emissions from eastern China have increased from 5.0 ± 0.4 Gg yr^{-1} in 2008 to 9.5 ± 1.0 Gg yr^{-1} in 2019. A continuous rise since 2015 stands in stark contrast to the large emissions reduction reported under the Chinese hydrochlorofluorocarbons production phase-out management plan. The cumulative difference in eastern China amounts to 47 ± 11 % of the global mismatch, and they suggest that the HFC-23 emissions rise in eastern China is more likely associated with known HCFC-22 production facilities rather than the existence of unreported, unknown HCFC-22 production. Thus observed discrepancies between top-down and bottom-up emissions could be attributed to unsuccessful factory-level HFC-23 abatement and subsequent inaccurate quantification of emission reductions.

Chemical and dynamical impacts on stratospheric trace species

Using Aura Microwave Limb Sounder satellite observations of stratospheric nitrous oxide (N_2O), ozone, and temperature from 2005 through 2021, **Prather, Froidevaux and Livesey (2023)** calculate the atmospheric lifetime of N_2O to be decreasing at a rate of -2.1±1.2 %/decade. This is occurring because N_2O abundances in the middle tropical stratosphere, where N_2O is photochemically destroyed, are increasing at a faster rate than the bulk N_2O in the lower atmosphere. If the observed trends in lifetime and implied emissions continue, then the change in N_2O over the 21st century will be 27% less than those projected with a fixed lifetime, and the impact on global warming and ozone depletion will be proportionately lessened. Because global warming is caused in part by N_2O, this finding is an example of a negative climate–chemistry feedback.

Tropospheric trends in long-lived source gases N_2O and chlorofluorocarbons cause trends in O_3 through changes in their reactive product gases. **Strahan et al. (2022)** found large changes in tropical upwelling at 10–5 hPa since 2012 that have strengthened the northern branch of the upper stratospheric transport circulation, dramatically altering the abundances of N_2O and its odd nitrogen product gases, NO_x and HNO_3. The increased upwelling is connected to stronger and more frequent Quasi-Biennial Oscillation easterly winds at 10 hPa and above, and simulations demonstrate that the dynamical impacts on these cycles explain the mid-stratospheric tropical O_3 increase and Arctic UpS O3 decrease since 2005.

The Australian New Year's fires and effects of stratospheric smoke injection

Large wildfires can generate pyrocumulonimbus clouds that transport smoke into the stratosphere and thus can have major impacts on the stratospheric aerosol budget and climate. **Katich *et al*. (2023)** analyzed 13 years of airborne observations to determine the chemical and physical compositions of pyrocumulonimbus smoke and to quantify its effects on stratospheric aerosols. These clouds are responsible for as much as 25% of the black carbon and organic aerosols now in the lower stratosphere and may become an even more important influence on future climate as the frequency and severity of extreme fires increase.

The catastrophic Australian New Year's (ANY) bushfires of 2019/2020 triggered multiple intense thunderstorms that injected record amounts of smoke and biomass-burning pollution directly into the lower stratosphere. Several publications used MLS and other satellite measurements to investigate the strong and extensive ANY-induced perturbations in the composition of the southern midlatitude stratosphere, which could not be reproduced by state-of-the-art chemical models. In a Perspective piece in Science, **Salawitch and McBride (2022)** reviewed those previous studies and summarized the current status of the debate in the atmospheric science community regarding the relative contributions from various fire-driven processes to the observed decline in total column ozone following ANY. They highlighted the shortcomings in our understanding of how wildfires affect stratospheric chemistry and dynamics. Two subsequent papers used MLS data to explore heterogeneous chemical processing on the organic aerosols released by wildfires. **Wang et al. (2023)** found evidence for chlorine activation in both middle and high latitudes after ANY under much warmer conditions than associated with chemical processing on typical stratospheric aerosols. **Solomon et al. (2023)** proposed that the solubility of hydrochloric acid (HCl) in oxidized wildfire smoke organics is extremely high under relatively warm stratospheric conditions, strongly enhancing heterogeneous chlorine activation rates and thus the potential for chemical ozone loss. These studies help elucidate the impacts of wildfires, which are becoming increasingly common as the climate changes, on Earth's protective ozone layer.

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 further understanding perturbations to the natural system and how they may better help inform nature-based solutions, greenhouse gas dynamics and feedbacks in high latitude areas, improve the prediction of species distribution, and develop new tools for ecological conservation, further elucidating connections across the Earth System and developing approaches that will improve predictive capabilities.

Ocean Biology and Biogeochemistry

A number of global priorities are focusing on the use of nature-based solutions for climate change, though the science is largely lagging the action. Earth System models can help provide some potential ecosystem responses to proposed climate mitigation scenarios. For instance, Fay et al. (2023) examined the impact of the Mount Pinatubo eruption (1991) on ocean oxygen and carbon budgets to better understand the ocean's biogeochemical response to this phenomenon. They found that the eruption led to cooler surface ocean temperatures, and increases in the ocean oxygen and carbon concentrations that persisted for many years. Unraveling the climate response to external perturbations like as the Mt. Pinatubo eruption is important as other analogous significant events, such as the Australian wildfires, induce similar responses which also have impacts on oceanic carbon and oxygen fluxes. Westberry et al. (2023) examined the extent and magnitude of atmospheric deposition-mediated effects on surface ocean ecosystems using global satellite ocean color products. The authors found that, while the responses to atmospheric dust deposition differed regionally, there were observed changes in phytoplankton biomass and/or changes in its physiological status or health. Ultimately, sustaining satellite observations will be critical to be able to measure the response of aquatic ecosystems to any type of climate mitigation intervention, in particular its continued ability to effectively sequester carbon for long time scales. Brewin et al. (2023) summarized a number of emerging priorities related to observation requirements for the next decade, and provided a comprehensive scientific roadmap on how satellite remote sensing could help monitor the ocean carbon cycle and its links to other parts of the Earth System.

Terrestrial Ecology

Shifts in Arctic climate have impacted the vegetation's CO_2 uptake rate, and recent research by Watts et al. (2022) highlighted the heterogeneity that exists across tundra and boreal wetlands with regards to net ecosystem CO_2 exchange (NEE) and CH_4 emissions. The authors used a satellite data-driven process- model for northern ecosystems, coupled with measurements from >60 tower eddy covariance (EC) sites, to analyze greenhouse gas fluxes for the entire Arctic- boreal zone between 2003–2015. Across the domain, the model indicated an overall average NEE sink of −850 Tg CO_2- C yr^{-1}; Eurasian boreal zones, especially those in Siberia, contributed to a majority of the net sink. In contrast, the tundra biome was relatively carbon neutral (ranging from small sink to source). Regional CH_4 emissions from tundra and boreal wetlands (not accounting for aquatic CH_4) were estimated at 35 Tg CH_4- C yr^{-1}. Accounting for additional emissions from open water aquatic bodies and from fire, using available estimates from the literature, reduced the total regional NEE sink by 21% and shifted many far northern tundra landscapes, and some boreal forests, to a net carbon source. This assessment, based on *in situ* observations and models, improves our understanding of the high- latitude carbon status and also highlights the continued need for integrated site-to-regional assessments to monitor the vulnerability of these ecosystems to climate change.

Liu et al. (2022) explained the slower rate of increasing annual net CO_2 uptake in northern areas with higher tree cover, especially in central and southern boreal forest regions, as a result of differential CO2 respiration/uptake throughout the growing season, potentially induced by climate change. Using estimates constrained from atmospheric observations from 1980 to 2017, they found that the increasing trends of net CO_2 uptake in the early-growing season are of similar magnitude across the tree cover gradient in the Northern High Latitudes (NHL). However, the trend of respiratory CO_2 loss during the late-growing season increases significantly with increasing tree cover. This results in a slower rate of increasing annual net CO_2 uptake in areas with higher tree cover, especially in central and southern boreal forest regions. The magnitude of this seasonal compensation effect explains the difference in net CO_2 uptake trends along the NHL vegetation- permafrost gradient. Such seasonal compensation dynamics are not captured by dynamic global vegetation models and calls into question projections of increasing net CO_2 uptake as high latitude ecosystems respond to warming climate conditions.

Land Cover/Land Use Change

The COVID-19 pandemic has had a widespread impact on human well-being, livelihoods, communities, and economies globally over the past three years, affecting over half a billion people and causing millions of deaths. Vadrevu et al., (2022) conducted a study on the COVID impacts on vegetation fires and emissions in South/Southeast Asia (S/SEA). They used the NASA-NOAA Suomi NPP vegetation fire data to address the information gap in understanding fire incidences, burnt area, vegetation types affected, and particulate matter emissions during COVID-19 in the region. The results showed a decline in fire counts ranging from −2.88% to 79.43% in S/SEA during March-May 2020, with some exceptions in specific countries. The burnt area also decreased from −0.8% to 92%, with agricultural landscapes experiencing more burning than forests. The authors also reported a decline in fire related particulate matter emissions in both S/SEA during 2020 (COVID year), compared to 2019 (pre-pandemic year). The study provides valuable insights for fire management and mitigation in the region. In another study, Piquer-Rodríguez et al. (2023) examined the observed effects of the pandemic on various land systems across the world, focusing on economic, health, and mobility dimensions. Through six vignettes from different continents, the researchers analyzed the impacts using the lens of socio-ecological resilience and the telecoupling framework. The results showed that the pandemic's effects have been context-specific and unevenly distributed, dependent on the connections between land systems worldwide. The study suggested that the pandemic served as "natural experiments" to better understand how global shocks affect local and regional landscapes and land systems, disrupting existing connections and forging new ones between people and land.

Biodiversity and Ecological Conservation

BioSCape

In fall 2023, NASA will conduct its first airborne campaign focusing exclusively on terrestrial, freshwater, and marine biodiversity. Called the Biodiversity Survey of the Cape or BioSCape, it will take place in the Greater Cape Floristic Region of South Africa. The very high terrestrial and marine species richness and endemism of this area, along with the shrubby and open nature of its fynbos vegetation, will test the ability of remote sensing to characterize the high biodiversity. NASA will deploy three imaging spectrometers (PRISM, AVIRIS-NG, and HyTES), operating from the ultraviolet through the thermal infrared regions of the electromagnetic spectrum, and a full waveform lidar (LVIS) aboard two aircraft to detect floristic biodiversity and discern its impacts on the functioning of local ecosystems as well as their provision of ecosystem goods and services to society. While initiated as a NASA Biological Diversity research activity, the conservation implications of BioSCape have driven the development of applications elements under the leadership of the NASA Ecological Conservation Program. Slingsby et al. (2023) used South Africa's Cape Floristic Region as a case study for an iterative and regional ecological forecasting framework combining in-situ and remote sensing observations and models to address decision maker needs for information on landscape-level change detection, ecosystem function, fire, and plant demography and distribution. Essentially, they proposed a forecasting framework for BioSCape and future continuity work. Ma et al. (2022) investigated the potential for deep learning models to perform vegetation state forecasting in open ecosystems, with the fynbos shrublands of the Cape Floristic Region serving as their model open ecosystem. They found that the Convolutional long short-term memory (ConvLSTM) model outperformed others in terms of accuracy of vegetation state (i.e., NDVI) forecasting. Inputs to the model were time series of NDVI images derived from MODIS. Grasslands and shrubby open ecosystems have long been a challenge for satellite remote sensing. Lewinska et al. (2023) addressed an aspect of this challenge in a study applying a new statistical approach PARTS, which explicitly accounts for temporal and spatial autocorrelation in trends. Teasing out these autocorrelations is critical to determine the reality of remote sensing-derived trends over time in green vegetation, non-photosynthetic vegetation, and soil fractions.

New Tools and Other Resources for Biological Diversity and Ecological Conservation Efforts

Trait databases are becoming increasingly popular and necessary sources of organismal functional information for use in studies and applications involving remote sensing. Gerstner et al. (2023) compiled from multiple sources Frugivoria, a trait database with ecological, life-history, morphological, and geographical traits for fruit-eating mammals and birds in the moist forests of Central and South America. Of note, it also includes a cross-taxa subset of shared traits. The soilborne fungal *Fusarium oxysporum* species complex constitutes one of the greatest threats to global agriculture and is a significant driver of food insecurity around the globe. Calderon et al. (2023) generated a publicly-available interactive web map depicting *F. oxysporum* occurrences. This map provides foundational location information for a NASA Biological Diversity project combining satellite remote sensing, aerosol transport modeling, and comparative genomics to

determine whether *F. oxysporum* spores can survive and transit very long distances on currents of atmospheric dust. The map is available at the link below.
https://experience.arcgis.com/experience/1e6014e6634948808a283d0a3b147bfe/

In order to support a series of both Biological Diversity and Ecological Conservation projects seeking to determine the distributions and abundances of penguin species in the Antarctic region, Che-Castaldo et al. (2023) outlined the Antarctic Penguin Biogeography Project, which seeks to bring together all that is known about the distribution and abundance of Antarctic penguins and make this information freely available to both the research and management communities. The project includes the Mapping Application for Antarctic Penguins and Projected Dynamics (MAPPPD) application at https://www.penguinmap.com, a search and visualization tool for policy makers as well as mapppdr, an R package for the research community. These tools constitute one-stop shops for those seeking information on the whereabouts and numbers of these top predators of the Antarctic. Smith et al. (2023) examined climate impacts on three species of vital importance to West Coast fisheries: Pacific sardine (*Sardinops sagax*), swordfish (*Xiphias gladius*), and albacore (*Thunnus alalunga*). Their results indicate a predominantly polar shift in the future distribution of all three species, which is anticipated to have significant impacts to fisheries. This work also serves as a primer for how to combine observations and models in frameworks characterized by hindcasts, reanalysis, forecasts, and projections to meet the needs of fishery managers.

Modeling species distributions through tools such as species distribution models, ecological niche models, habitat suitability models, etc.—with covariates derived from satellite remote sensing of environmental factors—is one of the oldest and more mainstream uses of NASA satellite products for both improved biodiversity understanding and conservation applications. Johnson et al. (2023) updated the Wallace Ecological Modeling Application's v2.0 vignette. Wallace is an R-based GUI application for building species distribution models that is open, accessible, expandable, flexible, interactive, instructive, and reproducible. A module of Wallace allows one to upload one's own continuous, numerical, or categorical variable raster datasets. Song and Estes (2023) took on the challenges of sensitivity to sampling patterns and over-fitting in species distribution models using presence-only data of species occurrences with their Isolation Forest (iForest) algorithm ISTDM package. It fits models by describing unsuitable as opposed to suitable conditions. Song et al. (2023) devised a three-stage ensemble method for land-cover mapping for improved satellite land cover maps over hard-to-classify, data-sparse landscapes with northern Tanzania as a case study.

<u>Section 1.1.9.3</u> 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.

<u>Sea Ice in the Climate System</u>

The indicators of rapid climate change in the polar regions (record sea ice loss, warming sea surface temperatures, and an extended sea ice melt season) each hold a key to determining the puzzle of how surface turbulent fluxes need to be better evaluated and represented within existing climate models to better predict these phenomena moving forward. Currently, there are large spreads between existing climate models in present day sea ice loss, turbulent fluxes and wintertime warming.

In recent decades, the Arctic has experienced rapid atmospheric warming and sea ice loss, with an ice-free Arctic projected by the end of this century. Cyclones are synoptic weather events that transport heat and moisture into the Arctic, and have complex impacts on sea ice, and the local and global climate. However, the effect of a changing climate on Arctic cyclone behavior remains poorly understood. *Parker et al. (2022)* used high resolution (4 km) regional modeling techniques and downscaled global climate reconstructions and projections to examine how recent and future climatic changes alter cyclone behavior. Results suggest that recent climate change has not yet had an appreciable effect on Arctic cyclone characteristics, though future sea ice loss and increasing surface temperatures drive large increases in the near-surface temperature gradient, sensible and latent heat fluxes, and convection during cyclones. This study highlighted that cyclones are highly sensitive to sea ice and atmospheric conditions in the Arctic, and changes in cyclone characteristics are most pronounced over areas with the greatest change in sea ice concentration. As such, current efforts to limit climate change and sea ice loss are paramount for mitigating the impacts of extreme polar weather in regions of significant ice loss, such as the Barents, Bering, and Chukchi seas.

The mass balance of the Antarctic ice sheet is intricately linked to the state of the surrounding atmosphere and ocean. As a direct result, improving projections of future sea level change requires understanding change in the Antarctic atmosphere and Southern Ocean, and the processes that couple these systems. *Trusel et al. (2023)* examined the influence of sea ice cover on the overlying atmosphere and subsequently the surface mass balance (SMB) of the adjacent Antarctic ice sheet by investigating these processes both over the observational era using the ERA5 atmospheric reanalysis and in ensemble simulations of the Community Earth System Model 2.1 (CESM2) where only sea ice coverage is altered. Comparing extreme high and low sea ice over the satellite era in ERA5 reveals atmospheric and ice sheet SMB anomalies that largely mirror anomalies simulated by CESM2 in response to sea ice loss. Results highlight significant near surface atmospheric warming in response to sea ice reductions, which are particularly pronounced in non-summer seasons and driven by significant ocean-to-atmosphere turbulent heat fluxes. These results indicate that underestimation of Antarctic sea ice, which is common in many current generation coupled climate models, may lead to overestimation of the ice sheet SMB and therefore underestimation of Antarctica's contributions to global sea level.

Sea ice thickness is a key property of the sea ice cover, and is highly variable in both the Arctic and Antarctic. One of the simplifying assumptions used in simulating sea ice in global climate models is representing the variation in ice thickness with a set number of thickness categories. Most models default to five thickness categories, though little has been done to explore the effects of the resolution of this distribution (number of categories) on sea-ice feedback in a coupled model framework and resulting representation of the sea ice mean state. *Smith et al. (2022)* explored this hypothesis using sensitivity experiments in CESM2 with the standard 5 ice thickness categories and 15 ice thickness categories.More thickness categories in the model results in significantly more simulated Arctic sea ice, but only slight increases in Antarctic sea ice. This is primarily because the model estimates that the ice is weaker, and so more of it piles up to result in thicker ice in the Arctic. Modeled variability in ice thickness is also compared with thicknesses from satellite observations (ICESat-2). In the current version of the model, increasing the number of thickness categories does not improve the comparison with observations.

Land Ice in the Climate System

The land ice contribution to global mean sea level rise has not yet been sufficiently 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. Additionally, incorporating natural phenomena such as seasonality and ice-ocean interactions remain some of the largest challenges facing the modeling community who are striving to better constrain sea level rise uncertainties.

The potential contribution of ice sheets remains the largest source of uncertainty in predicting sea-level due to the limited predictive skill of numerical ice sheet models, yet effective planning necessitates that these predictions are credible and accompanied by a defensible assessment of uncertainty. While the use of large ensembles of simulations allows probabilistic assessments, there is no guarantee that these simulations are aligned with observations. *Aschwanden & Brinkerhoff (2022)* presented a probabilistic prediction of 21st century mass loss from the Greenland Ice Sheet calibrated with observations of surface speeds and mass change using a novel two-stage surrogate-based approach. Their results suggest a sea-level contribution ranging from 4 to 30 cm at the year 2100, providing the assumption that the chosen ice sheet model's physics in this study represent reality.

The Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE) combines 50 independent satellite-based estimates of ice sheet mass balance to present a new, reconciled 29-year record of observed ice sheet mass balance. By measuring changes in the volume, gravitational attraction, and ice flow of Greenland and Antarctica from space, we can monitor their mass gain and loss over time. *Otosaka et al. (2023)* presented a new record of the Earth's polar ice sheet mass balance, produced by aggregating 50 satellite-based estimates of ice sheet mass change from 1992-2020. Results were used by the AR6 sea level rise assessment to show that the polar ice sheets have lost ice in every year of the satellite record, and the seven worst melting years have occurred during the past decade. Ice losses have accelerated at both ice sheets over this 29-year record, and the rate of ice loss is now 5 times higher in Greenland and 25% higher in Antarctica compared to the early 1990s. Together, Greenland and Antarctica now account for a quarter of all sea level rise, which represents a fivefold increase since the 1990's.

Sea-level rise projections rely on accurate predictions of ice mass loss from Antarctica. Climate change promotes greater mass loss by destabilizing ice shelves and accelerating the discharge of upstream grounded ice, and this mass loss is further exacerbated by mechanisms such as marine ice sheet instability and marine ice cliff instability. However, the effect of basal thermal state changes of grounded ice remains largely unexplored. *Dawson et al. (2023)* used numerical ice sheet modeling to investigate how warmer basal temperatures could affect the Antarctic ice sheet mass balance. They found that a warmer basal thermal state could increase mass loss from the ice sheet, which highlights the need to accurately resolve basal temperatures, and idealized basal thawing experiments run over 100 years resulted in increased mass loss. Most notably, frozen-bed patches could be tenuously sustaining the current ice configuration in parts of East Antarctica. These results highlight the need for advances in modeling the processes leading to thawing and the ice sheet response to environmental forcing.

Earth's ice sheets are subject to seasonal and long-term fluctuations in total ice thickness that are not due to actual ice mass changes. These height changes reflect changes in the air content of the porous firn layer at the top of the ice sheet where snow that falls is slowly buried and being densified into solid ice at depth. To assess ice sheet mass balance, firn air thickness fluctuations must be removed from satellite altimetric measurements (such as ICESat-2) of thickness change. *Medley et al. (2022)* present new simulations of firn processes over the Greenland and Antarctic ice sheets (GrIS and AIS) using the Community Firn Model and atmospheric reanalysis variables for more than four decades. They found that seasonal volume changes associated with firn air content are on average approximately 2.5 times larger than those associated with mass fluxes from surface processes for the AIS and 1.5 times larger for the GrIS; however, when averaged over multiple years, ice and air-volume fluctuations within the firn column are of comparable magnitudes. Between 1996 and 2019, the Greenland Ice Sheet lost nearly 5 % of its firn air content, indicating a reduction in the total meltwater retention capability. Nearly all (94 %) of the meltwater produced over the Antarctic Ice Sheet is retained within the firn column through infiltration and refreezing.

Surface-mass-balance (SMB) and firn-densification (FD) models are widely used in altimetry studies as a tool to separate atmospheric-driven from ice-dynamics-driven ice-sheet mass changes and to partition observed volume changes into ice-mass changes and firn-air-content changes. Systematic ice-sheet-wide repeated ice-surface-height measurements from ICESat-2 (the Ice Cloud, and land Elevation Satellite, 2) allow for the measurement of surface-height change of the Greenland ice sheet at quarterly resolution and compare the measured surface-height differences directly with those predicted by three FD–SMB models). *Smith et al. (2023)* investigated the models' accuracy in predicting atmospherically driven height changes by segregating the data by season and elevation, and based on the timing and magnitude of modeled processes in areas where minimal ice-dynamics-driven height changes are expected. This study demonstrates one of the first applications of altimetry-difference data to the validation of surface-mass-balance and firn-densification models (and, to the authors' knowledge, the first in Greenland). It demonstrates that the three models evaluated account for a large fraction of the observed height change in the low-elevation, high-melt areas of the ice sheet, but two of the three do not accurately account for the observed changes in higher elevation areas where melt is less common.

Oceans in the Climate System

The Physical Oceanography program in the CVC Focus Area aims to improve both 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 with numerical models of ocean physics through various data assimilation, integration, and machine learning approaches.

Estimating the Circulation and Climate of the Oceans

While numerical weather forecasting also involves data assimilation, there are important differences in estimating the state of the ocean, where conservation of physical properties such as heat, salt, or momentum, require alternative data assimilation approaches. Such conservation is crucial to the understanding of the ocean's role in long term climate change but is of little importance for weather forecasts, as their violation has no impact on short-range prediction skill. NASA supports production of a robust estimate and evolution of ocean and sea ice state through the Estimating the Circulation and Climate of the Ocean (ECCO) framework (https://ecco-group.org). ECCO integrates nearly all existing ocean satellite and in situ data constrained by the conservation laws of physics, to provide a description of the ocean circulation over the past three decades, as well as the evolution of sea ice and changes in the ocean biogeochemistry (*ECCO Consortium, 2021*).

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 interactions, ocean water cycle, carbon cycle and biogeochemical changes. This year in particular, the ECCO framework has been used to understand the natural/internal variability of the global ocean circulation and changes in the AMOC (*LeBras et al. 2023*), the partition between water routes in the global overturning circulation (*Rousselet et al. 2022*), variability in the formation of deep cold water in Antarctica's Weddell Sea (*Bailey et al. 2023*), sea level rise across various coastal regions across the globe (*Han et al. 2023, Frederikse et al. 2022, Piecuch et al. 2022, Adams et al. 2023*), and biogeochemical runoff from the Mackenzie river drives intense coastal Arctic Ocean CO_2 outgassing (*Bertin et al. 2023*). ECCO machinery has been instrumental in OSSEs and future satellite mission designs (*Torres et al. 2023*).

Projecting coastal sea level rise from NASA's Sea Level Change Team

As NASA faced increasing demand for sea level information, the agency assembled the centralized, multidisciplinary NASA Sea Level Change Team (N-SLCT), consisting of leading experts in the fields of ocean physics, geodesy, cryosphere, hydrology, modeling, statistics, and science communication. The team transcends barriers among different disciplines, develops integrated views of sea level both today and in the future, and makes our latest discoveries useful to the public and decision makers (*Vinogradova and Hamlington 2022*). N-SLCT delivers practical and useful sea level information to national, state, and local practitioners and decision-makers through a dedicated portal at https://sealevel.nasa.gov, and works with communities to understand and use sea level information and projected state of future climates (e.g., Application Guide for the 2022 Sea Level Rise Technical Report". See more at the new "Science to Action" platform of the portal.

This year N-SLCT collaborated with the United Nations Rising Nations Initiative (UN RNI) and the Global Center for Climate Mobility to aid international efforts to preserve sovereignty of the Pacific atoll countries impacted by sea level rise. Based on the latest satellite and in situ observations and state-of-the-art scientific understanding, N-SLCT developed a technical assessment of future sea level rise and associated impacts for Tuvalu (*Adams et al. 2023*). The assessment was presented at various forums, including U.N., ambassadors, the government and the public of Tuvalu, and is meant to serve as the informational foundation to prepare the low-lying island nations for a changing climate.

In addition to island nations, N-SLCT produced a wide range of sea level information for the coastal regions of the United States. For example, *Hamlington et al. (2022)* used satellite and tide gauge data to project sea level to 2050 – a time horizon particularly relevant to stakeholders in the U.S. They find that future sea level for the coastal United States tracks near high-end model projections, highlighting the need to continue monitoring of coastal sea level rise. High rates exceeding 10 mm/yr (the highest over the last 120 years) along the U.S. coast, particularly U.S. Southeast and Gulf coast were also reported by *Dangendorf et al. (2023)*. Accelerated rates were linked to the regional ocean dynamics, which will further benefit from the analysis of SWOT sea level data with spatial resolution about 50 m near the coasts.

To improve prediction on even shorter time horizons, *Frederikse et al. (2022)* leveraged ECCO's adjoint/machine learning capabilities to project sea level rise seasonal time scales. First results by *Frederikse et al. (2022)* show promise and positive prediction skill up to 6-month lead time for the seasonal hindcasts of sea level near Charleston, NC. In addition, continued effort to include 'missing physics and dynamical coupling' that will improve future projections included quantification of the impacts of atmospheric rivers (pressure) on sea level by *Piecuch et al. (2022)*, as well outflows of major rivers, e.g. Rio de la Plata (*Piecuch 2023*).

<u>The Integrated Earth System & Modeling</u>

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

Siberia experienced exceptional warmth during the spring of 2020, which followed an unusually warm winter over the same region. *DeAngelis et al. (2023)* combined MERRA-2 reanalysis and ensemble of simulations from NASA's GEOS atmospheric model to investigate the drivers of this unusual spring warmth from the perspective of atmospheric dynamics and remote influences. They found that the warm anomalies were associated with separate quasi-stationary Rossby wave trains emanating from the North Atlantic in April and May. The wave trains are shown to be extreme manifestations of the dominant modes of spring subseasonal meridional wind variability over the Northern Hemisphere. In both April and May, the wave trains were likely forced from an upstream region including eastern North America and the western North Atlantic. Analysis with a stationary wave model shows that transient vorticity flux forcing over and downwind of the North Atlantic, which is strongly related to storm activity caused by internal variability, is key to generating the wave trains, suggesting limited subseasonal predictability of the Rossby waves and hence the exceptional Siberian warmth. The results also suggest that anomalous tropical atmospheric heating contributed to the unusual warmth in Siberia through a teleconnection involving upper-troposphere dynamics and the mean meridional circulation. This tropical–extratropical teleconnection offers a possible physical mechanism by which anthropogenic climate change influenced the extreme Siberian warmth.

The remarkable eruption of the Hunga Tonga-Hunga Ha'apai (HTHH) underwater volcano on 15 January 2022 injected a record amount of water (~150Tg) directly into the stratosphere. This has exerted a significant impact on stratospheric composition and circulation. *Coy et al. (2022)* presented a study on stratospheric circulation changes in response to the HTHH eruption as captured by the MERRA-2 and the M2-SCREAM reanalysis fields. The changes in temperature, wind, and circulation due to HTHH were tracked through comparisons of the first six months of 2022 with the previous 42 years. Examination of the data assimilation process shows that at 20 hPa the thermal observations were forcing significant cooling, compensating for the absence of the excess stratospheric moisture in the model used for the reanalysis. In response to this cooling the atmosphere adjusted by creating strong westerly winds above the temperature anomaly and large changes to the downward and poleward mean meridional circulation.

Chemistry/climate modeling advances

Climate change is the result of the aggregate effect of several individual forcing agents changing the radiative balance at the top of the atmosphere over time. Over the historical period, since the pre-industrial era, greenhouse gases (GHG) and aerosols have provided the largest positive and negative forcings, respectively. However, the relationship between

GHG and aerosols have rapidly changed in the last decades. *Bauer et al. (2022)* used the GISS ModelE to investigate the connection between emissions, atmospheric composition and climate forcing over the CMIP6 historical period (1850–2014) and future radiative forcing projection for four Shared Socioeconomic Pathway (SSP) scenarios for 2015–2100: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. They found that over the CMIP6 historical period, aerosols provided the largest negative forcing compared to all other climate forcing via their ability to absorb or scatter solar radiation and alter clouds. Aerosols played an important role in counterbalancing GHG warming and were at maximum effect in the 1980s. Aerosol forcing in the GISS model has reached its turning point, switching from globally increasing to a decreasing trend in the first decade of the 21st century. As projected by the GISS ModelE, following the SSP scenarios, aerosols will only counterbalance 0%–20% of GHG forcing by the end of this century.

Climate prediction advances

Melting of the Greenland and Antarctic ice sheets is one of the most uncertain potential contributors to future climate change. Meltwater from Greenland might be expected to initiate a climate response that is distinct from that associated with Antarctic meltwater. Which one might elicit a greater climate response, and what mechanisms are involved? To explore these questions, *Li et al. (2023)* employed GISS-E2.1 to address the comparative role of Greenland and Antarctic meltwater in the climate system and explore differing mechanisms at work in each hemisphere. The study found that in both hemispheres, meltwater drives atmospheric cooling and sea ice expansion, and strengthens Hadley and Ferrel cells. Greenland meltwater induces a slowdown of the Atlantic meridional overturning circulation (AMOC) and a cooling of the subsurface ocean in the northern high latitudes. Antarctic meltwater induces a slowdown of the Antarctic Bottom Water formation and a warming of the subsurface ocean around Antarctica. Both the Greenland and Antarctic ice sheets have been melting at an accelerating rate over recent decades. The climate response is linear for low melt rates. However, as melt rates increase to 5000 Gt yr^{-1}, the climate response becomes nonlinear. In the Northern Hemisphere, the climate response is super-linear at high Greenland melt rates, due to a collapsed AMOC. In the Southern Hemisphere, the climate response is sublinear at high Antarctic melt rates, due to the halting of the northward expansion of Antarctic sea ice by warm surface waters. As the century proceeds, Antarctic meltwater will likely become increasingly dominant than that of Greenland meltwater, leading to atmospheric cooling, Antarctic sea ice expansion, and contraction and warming of the Antarctic Bottom Water. Greenland meltwater will lead to smaller changes in the Northern Hemisphere, than those in the Southern Hemisphere due to Antarctic meltwater.

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. 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. In 2023 ESI observed an increase in publications attempting to quantitively identify features and processes that can be linked to an increased likelihood of an event occurring. By better understanding how these features and processes can be detected and how they link to the event being studied, ESI takes a step closer to being able to quantitively forecast these events.

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 two types of hazards: volcanoes, and landslides.

Earthquakes

Identifying the methods for monitoring and measuring earthquakes and the seismic cycle are useful in mitigating and forecasting future events. Hill et al., (2023, Nature) used lake-filling events in the area of the SAF as a natural laboratory to understand how mass loading can impact seismicity. They identified that the increased Coulomb stress change caused by hydrologic loads from changing lake levels can increase Coulomb stress by several hundred kilopascals and fault-stressing rates by more than a factor of 2, which the author suggest is likely sufficient for earthquake triggering. This model demonstrates how impactful rapid changes in mass loads of any type, whether natural or anthropogenic, can trigger earthquake activity.

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. This year four different research groups used four very different methods to better forecast the likelihood of a volcanic eruption.

Ramsey et al., (2023) presents a new statistical approach to accurately detect subtle volcanic thermal anomalies automatically in TIR data and how this information can be used to forecast future volcanic activity. They performed this study on the twenty-two-year archive of ASTER TIR data with over 5 different volcanoes with >5000 unique acquisitions with 93% accuracy. They found that small subtle thermal features served as a precursory signal in ~81% of eruptions; the algorithm's results create a framework for classifying future eruptive styles.

Gonzalez-Santana et al., (2022) used InSAR data to explore the links between volcanic activity and flank creep behavior at Pacaya Volcano. They found that large transient flank instabilities occurred during vigorous eruptions in 2010 and 2014, but not during times of similarly elevated activity in 2007–2009 and 2018–2020. It was also determined that the opening of new vents outside the summit area, irrespective of whether this marks the start or a transition in an eruption, can initiate transient flank creep as detected in 2010 and 2014. The authors suggest that the opening of new magma pathways might provide forewarning for an increased likelihood of renewed or accelerating flank creep at Pacaya.

Albright and Gregg (2023) applied a reformulated ensemble Kalman filter (EnKF) to improve forecasting applications using volcanic deformation determined from GPS and InSAR data. They simulated observations of how the ground surface moves in response to an expanding underground magma reservoir, and then passed those data through several versions of the EnKF to see how closely the original conditions are reproduced. Ultimately different magma reservoir conditions produced similar observations at the surface which negatively impacted the EnKF's ability to precisely constrain the size and pressure state of the chamber. However, the authors maintain that the EnKF remains sensitive to key aspects of the magma system, including its mechanical stability.

Utami et al., (2022) used petrological and OMI data to examine the relationship between pre-eruptive excess volatiles and effusive to explosive eruption styles in semi-plugged volcanoes. They conducted a petrological analysis of the eruption products at Kelut Volcano and found that the sulfur budget of the 1990, 2007, and 2014 magmas show that the explosive events contained an excess fluid phase at pre-eruptive conditions. They authors propose that this led to their higher explosivity compared to the 2007 dome event. They suggest that the accumulation of excess fluid can be inferred from satellite monitoring records as well as changes in gravity of the plumbing system over time, all this information can contribute to creating a more accurate forecast of the eruptive style of future eruptions.

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.

Dille et al., (2022, Nature Geoscience) studied the effect urbanization has on the acceleration of large deep-seated tropical landslides detected by InSAR and photogrammetry. The basis for this study is that deep-seated landslides is regulated principally by changes in pore-water pressure in the slope, however urbanization can drastically reorganize the surface and subsurface hydrology as well as slope stability in a previously unknown manner. They found that over decadal timescales the sprawl of urbanized areas led to the acceleration of a large section of the landslide being studied. This suggests that the acceleration was driven by self-reinforcing feedbacks involving slope movement, rerouting of surface water flows and pipe ruptures in the urban areas. The authors mention that hillslopes in tropical cities are being urbanized at an accelerating pace and effective risk planning and mitigation is needed to account for landslides in these areas.

Handwerger et al., (2022) used InSAR data to quantify the sensitivity of 38 landslides to both record drought and extreme rainfall conditions that occurred in California between 2015 and 2020 to constrain the likelihood of landslide occurrence in diverse hydroclimatological conditions. They found that the landslides exhibited surprisingly similar behaviors and hydrologic sensitivity despite large differences in hydroclimate. These behaviors were characterized by faster (slower) than average velocities during wetter (drier) than average years, assuming the impact of drought has diminished. The authors suggest their findings may be representative of future landslide behaviors in California where precipitation extremes are predicted to become more frequent with climate change.

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.

Extreme Weather and Related Hazards Research

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.

After wildfire, steep slopes are vulnerable to runoff-induced post fire debris flows (PFDF). Orland *et al.* (2022: *Geophysical Research Letters*) have introduced a framework for PFDF hazard assessments using publicly available, global-scale inputs. This includes the first study of satellite derived rainfall data (the Integrated Multi-Satellite Retrievals for GPM (IMERG) Late Run v06B data set) for estimating PFDF initiation thresholds. Their model results demonstrate the feasibility of predicting PFDF hazards in near real-time on the global scale. Future improvements to satellite-borne rainfall intensity data and increased availability of PFDF occurrence data worldwide are expected to enhance model skill and applicability further. The intended use of this model is to provide near real-time situational awareness of PFDF hazards.

Sea level rise (SLR) is recognized as a major factor in increasing coastal flood risk in the future, but what are not well-recognized are the past and future impacts of climate-induced hydrological change (CHC) on flooding and relation to SLR. Getirana *et al.* (2023: *Water*

Resources Research) use two state-of-the-art models (the Hydrological Modeling and Analysis Platform, HyMAP, and the Noah-Multiparameterization Land Surface Model) to quantify how CHC affect southern Louisiana's water dynamics. They found that, over the past 28 years, CHC increased flood risk and SLR-induced flooding has been made worse by CHC. They conclude that, for prediction of future flood risk in river deltas and coastal areas worldwide, CHC must be considered in models and water management.

Borges *et al.* (2023: *Disaster Prevention and Management*) demonstrate methods to integrate earth observations (EO) into the Group on Earth Observations (GEO) Work Programme and the Committee on Earth Observation Satellites (CEOS) Work Plan. The climate crisis is forcing countries to face unprecedented frequency and severity of disasters. At the same time, there are growing demands to respond to policy at the national and international level. This paper demonstrates that EOs offer insights and intelligence to improve predictive capability for evidence-based policy development and decision-making to support key aspects of the Sendai Framework for Disaster Risk Reduction (DRR).

Water Availability Research

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.

Irrigation is the largest human use of freshwater, with major impacts on the water cycle, agriculture, ecology and land-atmosphere interactions. Uncertainties remain, however, in the timing and spatial distribution of irrigation. Nie *et al.* (2022: *J. Advances in Modeling Earth Systems*) assimilate satellite observations, the Moderate Resolution Imaging Spectroradiometer (MODIS) leaf area index (LAI), into the Noah-MP Land Surface Model to improve estimates of irrigation and associated fluxes. They show that this remotely sensed LAI improves simulations of irrigation and land surface model forecasts and projections of surface soil moisture, evapotranspiration, and gross primary productivity. This use of remote sensing integrated with models will help quantify the timing and distribution of global irrigation for better water management, predicting climate change impacts on future water availability, and simulating human influence on land-atmosphere interactions in coupled land to weather and climate models.

Irrigation impacts land hydrology, the atmosphere and their interactions. Lawston-Parker et al. (2023: *Hydrology and Earth System Sciences*) use a high-resolution, regional coupled modeling system to investigate the impacts of irrigation dataset selection on land–atmosphere coupling using a case study from the Great Plains Irrigation Experiment (GRAINEX) field campaign. Their results show that land-atmosphere coupling is sensitive to the choice of irrigation dataset and resolution and that the irrigation impact on surface fluxes and near-surface meteorology can be dominant or minimal. A consistent finding across several analyses was that even a low percentage of irrigation fraction (i.e., 4 %–16

%) can have significant atmospheric impacts, suggesting that the representation of boundaries and heterogeneous areas within irrigated regions is particularly important for the modeling of irrigation impacts on the atmosphere in this model.

On the regional scale, in the Colorado River Basin (CRB), climate uncertainties pose challenges to future long-term water management in seven U.S. states and Mexico. Whitney et al. (2023a: *Env. Modelling & Software*) presents a new web-based model, CRB-Scenario-Explorer, developed in collaboration with stakeholder water managers and scientists. This tool is used to provide interactive visualizations of future CRB hydrology for ranges of climate conditions, land use and deforestation. Whitney et al. (2023a) find that future CRB hydrology is more sensitive to climate uncertainties than forest disturbance uncertainties.

Whitney *et al.* (2023b: *J. Water Resource Plan. Management*) is a companion to the above paper, Whitney, Vivoni, and White (2023a: *Env. Modelling & Software*), that describes the new web-based model, CRB-Scenario-Explorer. In the present paper, Whitney et al. (2023b) described the stakeholder-engagement and top-down modeling to evaluate impacts of climate and land use / land cover (LULC) changes on future hydrology of the Colorado River Basin. They find that, under a scenario of future warm/wet climate for the CRB, forest reductions would lead to greater water supply efficiency. Under a scenario of hot/dry climate, though, increasing evapotranspiration and aridification of the American Southwest overwhelms any streamflow effect from forest reductions. Overall, according to stakeholder feedback, the iterative engagement and model development process described in Whitney et al. (2023b) has the potential to be tailored to address water security issues in the Colorado River and basins elsewhere. For instance, water managers that rely on snowpack amounts and the timing of snowmelt could look to the changing hydrograph from climate change and forest disturbance impacts to better prepare for any potential changes in reservoir operations.

Temperature and humidity forecasts are critical for many reasons, including storm prediction, water cycle modeling including evapotranspiration, and Earth System models in general. Reichle et al. (2023) find that medium-range weather forecasts of near-surface air temperature and humidity are improved by assimilating L-band SMAP land brightness temperatures into the NASA Goddard Earth Observing System (GEOS) model. The L-band SMAP is highly sensitive to surface soil moisture to a depth of 5 cm, and soil moisture impacts medium-range to seasonal forecasts. In the future, Reichle et al. foresee that integrating land and atmospheric analysis components into a single, strongly coupled land–atmosphere analysis may result in further improvements to forecasts. Nevertheless, the weakly coupled system as used in the present study already shows clear benefits and should be adopted in a future upgrade of the GEOS FP quasi-operational system. The experience that would be gained from having an SMAP Tb assimilation in a quasi-operational system will greatly facilitate further development and improvements.

McDermid *et al.* (2023: *Nature Reviews Earth & Environment*) review global irrigation and summarize how irrigation currently impacts key components of the Earth system, including surface temperature, precipitation, carbon emissions and ecology. Irrigation accounts for ~70% of global freshwater withdrawals and ~90% of consumptive water use, driving myriad Earth system impacts. They recommend that future irrigation research requires improvements to data products, tools and approaches, and better quantification of uncertainties. Combined with systematic uncertainty and sensitivity assessment, process-based model intercomparison projects that include irrigation will be useful in attributing observations of regional climate change. Model refinement will also come from satellite-based data products such as ECOSTRESS and, in the future, NISAR.

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.

WAD spent a lot of energy and investment supporting the NASA-NOAA-DOD Joint Effort for Data Assimilation Integration (JEDI) development. The Joint Center for Satellite Data Assimilation (JCSDA) is leading the JEDI project, which aims to create an integrated data assimilation system for the modern era. Using generic programming and object-oriented design, JEDI develops efficient, flexible, and user-friendly scientific software. It builds data assimilation algorithms in a generic manner, allowing their use across different centers, thereby streamlining software development and upkeep.

JEDI is widely accepted by operating centers of NOAA and Navy as the next generation data assimilation framework for weather forecasting. Increasingly it is also prototyped by NASA and NOAA for coupled ocean-atmosphere model for subseasonal to seasonal prediction systems. Because of the joint nature of the project, NASA's contribution including observations will flow to operational centers naturally. The joint data assimilation and prediction framework would streamline the weather and short-term climate prediction workflow and benefit the public by providing timely and skillful weather predictions and climate projections.

The following sections describe the progress made in understanding and improving the prediction of many weather related phenomena in the past year (2022-2023).

Development and Application of Data Assimilation Systems

The Joint Effort for Data Assimilation Integration (JEDI) Project: NASA is actively engaged in JEDI to enhance data assimilation for its Goddard Earth Observing System (GEOS) model, enabling scalability for future projects like coupled Earth system data assimilation. Two major releases were reached this year. First, JDI-FV3 was released in this period (https://github.com/JCSDA/fv3-jedi) and second, JDI Unified Forward Operator (UFO), which calculates observation-equivalent values from model forecasts was also released (https://github.com/JCSDA/ufo). A key innovation is UFO's separation of observation-related code from model-specific components, enabling parallel development and utilization by different teams. The use of JEDI observation data conventions has facilitated this approach. Progress has been substantial, with UFO supporting a wide range of satellite and conventional instruments, aligning closely with the current capabilities of the Gridpoint Statistical Interpolation (GSI) data assimilation scheme used in GEOS, and providing novel capabilities for emerging sensors such as TROPICS, TEMPEST, COWVR, Windborne stratospheric balloons, and commercial GNSS radio occultation data buys from Spire, PlanetiQ, and GeoOptics.

Community Radiative Transfer Model Release 3.0: The JCSDA Community Radiative Transfer Model (CRTM) is a fast, one-dimensional radiative transfer model and a key component of the JEDI infrastructure. CRTM is extensively employed in various applications, including numerical weather prediction and calibration-validation by federal agencies and universities. Its primary advantage lies in its role as a satellite simulator, accurately simulating satellite radiances through convolution of specific sensor response functions with a line-by-line radiative transfer model (LBLRTM), spanning spectral ranges from visible to microwave. The publicly released CRTM Version 3.0 expands its capabilities to encompass ultraviolet radiances and space-based radar sensors. Beyond radiance simulation, CRTM provides Jacobian outputs that enhance satellite observation interpretation for numerical weather prediction by quantifying how geophysical parameter changes affect simulated sensor measurements, thereby improving prediction accuracy and efficiency. The CRTM's development and effectiveness hinge on community engagement, facilitated by accessible programming, documentation, public domain licensing, GitHub access, and a pathway to operational integration, all aimed at fostering collaborative contributions and ongoing improvements.

Improved Representation of Hydrometeors in Radiative Transfer Models: Radiative transfer (RT) models have a wide range of applications in remote sensing, satellite data calibration, instrument design, and weather forecasts. Although the clear-sky simulations conducted by the RT models are relatively accurate, the accuracy of these models for simulating observations in cloud- and precipitation-affected (all-sky) conditions is limited. One of the main reasons for the inaccuracies in all-sky simulations is known to be the scattering databases used to calculate the optical properties of different cloud hydrometeors. Moradi et al. (2023) implemented and evaluated a large scattering database, computed using the Discrete Dipole Approximation (DDA) technique, into the JCSDA CRTM. The results showed that the simulations conducted using the DDA database are much more accurate than the corresponding simulations conducted using the Mie scattering lookup tables which assumes spherical particles for all hydrometeors.

SkyLab Releases JEDI-SkyLab Test and Application Files: JCSDA SkyLab provides roll-up software releases for integrated Earth system data assimilation capability via a unified end-to-end ecosystem including a single code build, workflow, data store, and diagnostics dashboard. Initial capabilities are demonstrated for the following components: atmosphere, ocean, sea-ice, soil moisture, snow, aerosols, and composition. SkyLab release 2.0 (October 2022) brings expanded observation types for the atmosphere-land experiment, a marine experiment with new instruments, and a composition experiment featuring new observations. The release also offers an environment built on SPACK-STACK 1.1.0, and extensive support for multiple system requirements. SkyLab release 3.0 (January 2023) brings significant enhancements, including a non-cycling 3D-Var ensemble of data assimilations (EDA) for atmosphere-land with more observation types, an aerosol data assimilation experiment, improved TROPOspheric Monitoring Instrument (TROPOMI) CO converter, expanded system support, and a substantial data store. SkyLab release 4.0 (April 2023) introduces key enhancements, such as updated observation converters for various satellite wind data, correlated observation errors for IASI and CRiS, and the inclusion of CO and NO2 3DVar assimilation using TROPOMI and MOPITT observations for trace gas analysis. SkyLab release 5.0 (July 2023) brings the utilization of CRTM v3.0 for satellite radiance observations, expanded monitoring for SSMIS, COWVR, and TEMPEST. Support is extended to the multiple new high performance computing (HPC) systems.

Developed and distributed by the JCSDA, JEDI is versatile and sophisticated enough for a variety of applications, from operational weather forecasting and atmospheric research on High Performance Computing (HPC) platforms to learning the fundamentals of data assimilation by running idealized toy models on a laptop. This data set provides example observation files, model backgrounds, and other input files needed to run a variety of JEDI applications, including the comprehensive suite of unit tests and example activities that are described in online tutorials.

Coupled Land-Atmosphere Data Assimilation: Reichle et al. (2023) introduced a weakly coupled land analysis into NASA's GEOS hybrid 4D-EnVar atmospheric data assimilation system to additionally assimilate L-band (1.4 GHz) brightness temperature observations over land from the NASA Soil Moisture Active Passive (SMAP) satellite mission. These SMAP radiances are highly sensitive to surface (∼0–5 cm) soil moisture. Retrospective assimilation experiments for boreal summer 2017 were conducted with the system at 50-km horizontal resolution. The SMAP assimilation is shown to mitigate errors in screen-level (2-m) specific humidity and temperature, with regional reductions in the root-mean-square errors (RMSE) of up to 0.4 $g \cdot kg^{-1}$ and 0.3 K, respectively. These improvements are somewhat smaller than those found in a precursor study that used the atmospheric analysis in the simpler, 3D-Var atmospheric assimilation configuration of the current GEOS reanalysis since the hybrid 4D-EnVar provides overall better near-surface background estimates than 3D-Var and therefore leaves less room for improvement. In the hybrid 4D-EnVar system with SMAP assimilation, forecasts of screen-level specific humidity and temperature have significantly improved anomaly correlation and RMSE (99% confidence) at lead times out to 5 days compared to the hybrid 4D-EnVar system without SMAP assimilation, with medium-range lead times extended by ∼3 hr for humidity and ∼2 hr for temperature. Slight but nevertheless significant improvements are also seen for temperature forecasts at the 925 and 850 hPa levels and lead times out to 4 days. Humidity forecasts at 925 and 850 hPa are improved out to 1.5-day lead time with 90% confidence.

Observing System Simulation Experiments, 4D-EnVar Scheme: Observing system simulation experiments (OSSEs) provide a realistic simulated framework for evaluation of data assimilation system properties and the potential impact of a particular observing system, current or future, on analysis and forecast accuracy. NASA's Global Modeling and Assimilation Office (GMAO) develops and maintains one of the most advanced OSSE systems in the world, which it employs routinely for basic research and to advance emerging data types toward operational implementation. El Akkraoui et al. (2023) have extended the GMAO OSSE framework to use a hybrid four-dimensional ensemble–variational (4D-EnVar) scheme instead of the original 3D-Var scheme. Use of the hybrid 4D-EnVar leads to a consistent reduction in the standard deviations of assimilation, background and forecast errors. Just as importantly, exploring the fourth (time) dimension within the assimilation window provides new opportunities for the use of OSSEs. For instance, the adequacy of the treatment of observations with high-temporal frequency can be directly assessed, and strategies for four-dimensional thinning of radiance data can also be explored to determine when such data have the most positive impact.

Observing System Simulation Experiments, Assimilating Hyperspectral Infrared Radiances from Geostationary Orbit: McGrath-Spangler et al. (2022) used the GMAO OSSE system to assess the impact of assimilating hyperspectral infrared (IR) radiances from geostationary orbit on numerical weather prediction, with a focus on the proposed sounder on board the Geostationary Extended Observations (GeoXO) program's central satellite. Infrared sounders on a geostationary platform would fill several gaps left by IR sounders on polar-orbiting satellites, and the increased temporal resolution would allow the observation of weather phenomena evolution. In addition to the full suite of meteorological observations in the GMAO OSSE system, the experiment additionally assimilated four identical IR sounders from geostationary orbit to create a "ring" of vertical profiling observations. Based on the experimentation, assimilation of the IR sounders provided a beneficial impact on the analyzed mass and wind fields, particularly in the tropics, and produced an error reduction in the initial 24 to 48 hours of the subsequent forecasts. Specific attention was paid to the impact of the GeoXO Sounder (GXS) over the contiguous United States (CONUS) as this is a region that is well-observed and as such is difficult to improve. The adjoint-based forecast sensitivity observation impact (FSOI) metric, computed across all four synoptic times over the CONUS, reveals that the GXS had the largest impact on the 24-h forecast error of the assimilated IR satellite radiances as measured using a moist energy error norm. Based on this analysis, the proposed GXS has the potential to improve numerical weather prediction globally and over the CONUS.

Improved Prediction of Storm Track and Intensity

Improving the Determination of Storm Intensity: With its seven-hour revisit time over the tropics, CYGNSS observations of ocean surface winds in the hurricane environment and inner core region facilitate both hurricane weather research and prediction studies. CYGNSS wind products have been assimilated into various research and operational numerical weather prediction models to demonstrate their utility in improving hurricane forecasting. One recent study demonstrated that the assimilation of CYGNSS data results in improved hurricane track and intensity simulations of Hurricanes Harvey and Irma (2017) through the enhanced representation of surface wind fields, hurricane inner-core structures, and surface fluxes (Pu et al. 2022). Examining major hurricanes in the 2018 and 2020 seasons (e.g., Florence and Michael in 2018 and Laura and Delta in 2020) the study indicates that the CYGNSS retrieved L2 wind speed has an influence on simulations of landfalling hurricanes comparable to that of Advanced Scatterometer (ASCAT) ocean surface wind. These research outcomes indicate that CYGNSS retrieved winds could be a valuable data source for research and operational uses to complement the available routine observations.

Combining GPM and Other Data for Extratropical Cyclone Analysis: While numerical simulations can help establish the role of extratropical cyclones in moisture transport leading to clouds and precipitation, evaluating and constraining these simulations require observations. Naud et al. (2023) divided satellite-based cloud and precipitation estimates in low-latitude extratropical cyclones into four distinct classifications based on CYGNSS latent and sensible heat fluxes. In the post-cold frontal region, stronger latent or sensible heat fluxes were associated with lower precipitation rates and higher cloud opacity, indicating more vigorous shallow convection. However, larger sensible heat flux cases displayed larger cloud fraction, while larger latent heat flux cases exhibited lower cloud fraction, which could indicate differing cloud morphologies. In the comma region of the cyclones, clouds and precipitation depended on both cyclone strength and moisture availability. Consistent with this, larger cloud amount and precipitation were found for strong fluxes in the post-cold frontal region, and weak or negative sensible heat fluxes, indicative of poleward warm advection, in the warm sector.

Building a Simple Model of Tropical Convective System Growth: The maximum areal extent of deep convective systems is driven by the stratiform anvil area since convective area is relatively small when systems reach peak size. Elsaesser et al. (2022) used satellite diabatic heating and convective-stratiform information mapped to convective systems, revealing that composite system maximum sizes occur at the temporal mid-point of system lifecycles, with both maximum size and duration correlating with peak heating above the melting level. However, the overall smooth composites are the average of highly variable system trajectories. On short (30-min) timescales, a simple analytical source-sink model of system area showed that growth occurs when detrained convective mass (inferred from the vertical gradient of diabatic heating and temperature lapse rates) and/or generation of convective area exceeds a sink term whose magnitude is proportional to the current cloud shield size. The model worked well for systems over land and ocean, and for systems characterized by varying degrees of convective organization and duration (1.5–35 hr, with correlations often >0.8 across lifetime bins). The model may support conceptual development and evaluation of prognostic climate model stratiform anvil area parameterizations.

Improved Forecasting of Mesoscale Convective Cyclones: The impact of adaptively thinned AIRS and CrIS hyperspectral infrared (IR) cloud-cleared radiances has been tested in the NASA GEOS data assimilation and forecast system. Previous work has shown the benefit of ingestion of these data in partially cloudy regions to improve forecasting of tropical cyclones. Building on this previous work, Ganeshan et al. (2022) show that the same technique can improve the representation of a broader range of such as polar lows or ‘medicanes’.

Advancing the Prediction of Precipitation

Using Observed Convection to Validate Models of Momentum Flux into the Stratosphere: The lack of observations makes it challenging to quantify the momentum flux transported from the troposphere into the lower stratosphere by gravity waves generated by convection. This limits our understanding of the stratosphere’s general circulation and the realism of simulations of the Quasi Biennial Oscillation. Some general circulation models have linked the momentum flux to the latent heating from subgrid scale convective precipitation, however, there is still a large uncertainty in the subgrid-scale convection in these models. Liu et al. (2022) applied the links between the momentum flux and convective latent heating directly to the convective precipitation derived from 16 years of TRMM Precipitation Radar observations in the tropics and subtropics. They computed the total and directional momentum flux at 100 hPa for individual convective gridboxes by using the TRMM Spectrum Latent Heating product and large-scale wind profiles from the ERA-Interim dataset. They provided the first estimates for the geographical distribution of momentum flux at 100 hPa in the tropics and subtropics from the observed convective sources, including the diurnal, seasonal, and interannual variations of the derived momentum flux, which can now be used for model validation.

<u>Combining GPM and Other Data to Analyze the Effect of Convection across the Tropopause:</u> Johnston et al. (2022) characterized the relationship of extratropical precipitation systems to changes in upper troposphere and lower stratosphere (UTLS) temperature and tropopause height within different environments. Precipitation features (PFs) observed by the Global Precipitation Measurement (GPM) Core Observatory were collocated with GPS radio occultation (RO) temperature profiles from 2014 to 2017 and classified as non-deep stratospheric intrusion (non-DSI; related to convective instability) or deep stratospheric intrusion (DSI; related to strong dynamic effects on the tropopause). Non-DSI PFs introduced warming (up to 1 K) in the upper troposphere, transitioning to strong cooling (up to −3.5 K) around the lapse rate tropopause (LRT), and back to warming (up to 2.5 K, particularly over the ocean) in the lower stratosphere. UTLS temperature anomalies for DSI events were driven predominantly by large scale dynamics, with major cooling (up to −6 K) observed from the mid-troposphere to the LRT, which transitioned to strong warming (up to 4 K) in the lower stratosphere. Small and deep non-DSI PFs typically resulted in a lower LRT (up to 0.4 km), whereas large but weaker PFs led to a higher LRT with similar magnitudes. DSI events were associated with larger LRT height decreases, with anomalies of almost −2 km near the deepest PFs. Importantly, non-DSI PF temperature anomalies show patterns similar to tropical convection, which bridges previous tropical research to extratropical barotropic convective impacts on UTLS temperatures.

<u>Using IMERG to Investigate MJO Precipitation Features:</u> Bai and Schumacher (2022) investigated how the Madden-Julian Oscillation (MJO) modulated the rainfall over the Maritime Continent in 89 MJO events during 2001-2019 using IMERG data. Daily and diurnal rainfall maxima on the east side of topography lagged the west side as the MJO passed. In addition, the pre-(post-)MJO rain was more convective(stratiform). Defining the timing and magnitude of diurnal rainfall by the maximum hourly rain rate, a single sharp peak was observed over the mountains around 19 Local Time(LT), a much broader delayed peak occurred over land to the west of topography, two peaks were observed over land to the east of topography at 15 and 02 LT, and rain peaked offshore from 03 to 07 LT. The contrasting east-west features were attributed to topographic influences on the moisture flux convergence of the mean column moisture by MJO-induced winds, while the MJO wind modulation of diurnal rainfall over most of the open ocean areas is insignificant.

<u>Landslide Hazards in the Lower Mekong Region:</u> Biswas et al. (2022) developed a region-specific dynamic landslide hazard system leveraging satellite-based Earth observation data to assess landslide hazards across the lower Mekong region and to improve near-real-time landslide hazard assessment. The system uses a set of landslide inventories from high-resolution optical imagery using advanced image-processing

techniques along with several dynamic explanatory variables (i.e., rainfall from GPM, soil moisture) and static variables (i.e., slope, relief, distance to roads, distance to faults, distance to rivers) for the model development phase. An extreme gradient boosting decision tree model was trained for the monsoon period of 2015–2019 and the model was evaluated with independent inventory information for the 2020 monsoon period. The model performance demonstrated considerable skill using receiver operating characteristic curve statistics, with Area Under the Curve values exceeding 0.95. The model was designed to use near-real-time data, and it can be implemented in a cloud computing environment for routine assessment of landslide hazards in the Lower Mekong region. This work was developed in collaboration with scientists at the Asian Disaster Preparedness Center as part of the NASA SERVIR Program's Mekong hub. The goal of this work is to develop a suite of tools and services on accessible open-source platforms that support and enable stakeholder communities to better assess landslide hazard and exposure at local to regional scales for decision making and planning.

<u>Global Landslide Forecasting System:</u> The Landslide Hazard Assessment for Situational Awareness (LHASA) model provides near-real-time estimates of potential landslide hazard and exposure around the world. Khan et al. (2022) introduced a precipitation forecast module into LHASA to complement the existing LHASA framework and provide landslide hazard products up to 3 days in advance at 1 km resolution. The model-based Goddard Earth Observing System-Forward Processing (GEOS-FP) precipitation forecast product is used as the forcing input for the model in place of the satellite-based Integrated Multi-satellitE Retrievals for Global Precipitation Mission product. Soil moisture and snow depth from the GEOS-FP assimilated product are also incorporated. The study period January 2020–January 2021 was used to test the model performance against the LHASA near real-time estimates at multiple spatiotemporal scales. The model was validated using a collection of rainfall-triggered landslide inventories from around the world as case studies to demonstrate the potential utility and limitations of this system. The rescaling of the GEOS-FP precipitation product is a critical step in incorporating the forecasted precipitation data within LHASA-Forecast (LHASA-F). Results indicate that for the case studies evaluated, the LHASA-F is generally able to resolve major landslide events triggered by extreme rainfall, such as from tropical cyclones. The analysis shows that landslide forecast outputs may be represented differently depending on the user's needs. The authors indicate that this framework serves as a first milestone in providing a global predictive view of landslide hazard.

<u>Improving Post-fire Debris Flows:</u> Orland et al. (2022) presented a framework that uses available satellite-based data, including GPM's IMERG Late Run product, to inform where post fire debris flows (PFDFs) may be elevated. Previous work establishes methods for PFDF hazard assessment, often relying on regional-scale parameterizations with in-situ rainfall measurements to categorize hazard as a function of meteorological and surface properties. To expand the methodology, the authors show a globally scalable approach to extend the benefit these models provide to new areas. They demonstrate that it is possible to identify the conditions relevant for PFDF-initiation processes across a variety of physiographic settings. Improvements to satellite-borne rainfall intensity data and increased availability of PFDF occurrence data worldwide are expected to enhance model skill and applicability further.

Flood Peak Discharge and Duration using IMERG and MRMS: Woods et al. (2023) used satellite-based IMERG V06 and ground radar-based Multi-Radar Multi-Sensor (MRMS) products as forcings for a distributed hydrologic model across the Continental United States. The output was compared using a methodology designed to assess the flood signals and characteristics generated by the model. By focusing on how well the model reproduced flood characteristics rather than fits with traditional bulk statistics, the research provided insights into satellite precipitation deficiencies. They found that satellite data have greater success at resolving lower magnitude flood events while tending to generate floods of longer durations, both beginning earlier and ending later than the ground radar reference.

Relating Latent Heating and Cloud Properties using a Model: Tao et al. (2022) reported on use of a cloud-resolving model to relate cloud properties and latent heating with cloud up-/downdrafts to make 15-day simulations for oceanic and continental environment. The results showed that condensation, deposition, and freezing occur mainly in moderate (3–5 $m\ s^{-1}$) to strong (>10 $m\ s^{-1}$) updrafts, evaporation and sublimation mainly in weak (1–2 $m\ s^{-1}$) to moderate downdrafts, and melting in moderate updrafts and downdrafts. Active updrafts covered only a small percentage of the model domain but contribute strongly to latent heat release, and carry most of the hydrometeors. Active updrafts with vertical velocities exceeding 1 and 2 $m\ s^{-1}$ account for more than 75% and 50%, respectively, of the condensation, deposition, and freezing in both the oceanic and continental cases. Active downdrafts with vertical velocity magnitudes exceeding $|1\ m\ s^{-1}|$ account for less than 40% and 25%, respectively, of the evaporation and sublimation. More evaporation and sublimation than condensation and deposition occur in the inactive cloud regions. Sensitivity tests show that model resolution had more impact than the microphysics on the simulated cloud properties in both cases.

Identifying Graupel and Hail Around the Globe: Le and Chandrasekar (2022) developed a graupel and hail (GH) identification algorithm for GPM DPR using a precipitation type index (PTI) defined for DPR using reflectivity, dual-frequency ratio, and storm top height data. The PTI effectively separated hydrometeor types and is calculated using measurements of reflectivity, dual-frequency ratio, and storm top height data. They reported that validation with the WSR-88D network over continental United States, during the Remote sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observations (RELAMPAGO) experiment, and against comparisons with the global lightning and hail precipitation maps generated using radar and radiometer on a global basis showed promise.

Developing a New Cluster Analysis Scheme for Precipitation: While analyzing TRMM precipitation data, Petty (2022) developed a simple, flexible, and robust algorithm for fully partitioning an arbitrary dataset into compact, nonoverlapping groups or classes, sorted by size, based entirely on a pairwise similarity matrix and a user-specified similarity threshold. There is no assumption that natural clusters exist in the dataset, although clusters, when present, may be preferentially assigned to one or more classes. As well, his method does not require data objects to be compared within any coordinate system but rather permits the user to define pairwise similarity using a wide range of criteria. The method is inductive in that prototypes identified in representative subset of a larger dataset can be used to classify the remainder.

Adding Machine Learning to GPROF: The Goddard Profiling Algorithm (GPROF) is used operationally to retrieve precipitation from all PMW sensors of the GPM constellation, serving as an essential component of the GPM processing pipeline. Pfreundschuh et al. (2022) introduced two neural-network-based, probabilistic implementations of GPROF: GPROF-NN 1D, which (like the current GPROF implementation) processes pixels individually, and GPROF-NN 3D, which employs a convolutional neural network to incorporate structural information into the retrieval. Despite using the same input information as GPROF, the GPROF-NN 1D retrieval improves the accuracy of the retrieved surface precipitation for the GPM Microwave Imager (GMI) from 0.079 to 0.059 mm h^{-1} in mean absolute error (MAE), from 76.1 % to 69.5 % in symmetric mean absolute percentage error (SMAPE) and from 0.797 to 0.847 in correlation. The improvements for the Microwave Humidity Sounder (MHS) are from 0.085 to 0.061 mm h^{-1} in MAE, from 81 % to 70.1 % in SMAPE, and from 0.724 to 0.804 in correlation. Comparable improvements are found for the retrieved hydrometeor profiles and their column integrals, as well as the detection of precipitation. Moreover, the ability of the retrievals to resolve small-scale variability is improved by more than 40 % for GMI and 29 % for MHS. The GPROF-NN 3D retrieval further improves the MAE to 0.043 mm h^{-1}; the SMAPE to 48.67 %; and the correlation to 0.897 for GMI and 0.043 mm h^{-1}, 63.42 %, and 0.83 for MHS. Despite superior accuracy, the single-core runtime required for the operational processing of an orbit of observations with the machine learning schemes is lower than that of GPROF.

Advancing Synthetic Hydrometeors for Better Radiative Transfer Modeling: Pellissier et al. (2023) tackled the problem of melting realistically structured synthetic snowflakes by developing the meshless-Lagrangian computational approach Snow Meshless Lagrangian Technique (SnowMeLT). SnowMeLT is capable of scaling across large computing clusters, and a collection of synthetic aggregate snowflakes from NASA’s OpenSSP database with diameters ranging from 2 to 10.5 mm were melted as a demonstration of the method. To properly capture the flow of meltwater, the authors carried out the simulations at relatively high resolution (15 µm), and a new analytic approximation was developed to simulate heat transfer from the environment without the need to simulate the atmosphere explicitly. The various melt stages have profound implications for radiative transfer modeling that is needed in both numerical models and satellite retrievals.

Integrating Aqua AIRS in a Real-Time Science-to-Application System to Support Severe Weather Forecasting: The 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. 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 and is optimal for low latency delivery of value-added products for applications. Through a partnership with JPL, SPoRT, and NUCAPS Algorithm developers, SPoRT integrated Aqua AIRS satellite sounding retrievals into their suite of satellite sounding products designed for use by the National Weather Service. A prototype science-to-applications system was developed to enable real-time processing of NASA's Aqua AIRS satellite sounding retrievals through the NUCAPS algorithm (i.e., NUCAPS-Aqua) to support weather forecasting applications (Berndt et al. 2023). The system was developed by adapting NASA CLIMCAPS (e.g., Community Long-term Infrared Microwave Combined Atmospheric Product System) science code to rapidly process NUCAPS-Aqua within 1 hour of the satellite overpass with the goal of benefiting NOAA NWS forecasting operations and facilitating end user product assessment during the 2022 Hazardous Weather Testbed Spring Experiment. The NUCAPS-Aqua algorithm preserves as much of AMSU as possible. by calculating the a-priori regression coefficients using 19 focus days covering all four seasons and include various extreme events. These coefficients were generated using all 1485 pristine AIRS channels and the 10 good AMSU channels. Key adaptations to the data pathway were necessary to process NUCAPS-Aqua in real-time including compatibility with NWS operational infrastructure, maintaining low latency, preserving retrieval quality, and dealing with the limitations caused by direct broadcast line of sight. Berndt et al. (2023) highlights two illustrative pre-convective cases analyzed by NWS forecasters during the 2022 HWT Spring Experiment are presented to qualitatively demonstrate the benefit of NUCAPS-Aqua as (a) special afternoon soundings that fill gaps in the observational network, (b) an additional observational tool to assess temporal trends in combination with NUCAPS-NOAA20, and (c) a complement to observational and model analysis.

<u>Applying Machine Learning to Estimating Precipitation Phase:</u> Das et al. (2022) used GPM Microwave Imager (GMI) and dual-frequency precipitation radar (DPR) together in a machine learning (ML) model to train and test the predictability and accuracy of using passive GMI-only observations together with ancillary information from a reanalysis and GMI surface emissivity retrieval products to infer convective/stratiform separation. Out of six ML models, the authors reported that four simple ones (support vector machine, neural network, random forest, and gradient boosting) and the 1-D convolutional neural network (CNN) model produce 90–94% prediction accuracy globally for five types of precipitation (convective, stratiform, mixture, no precipitation, and other precipitation), which is much more robust than previous similar efforts. The authors applied data augmentation (subsampling and bootstrapping) to handle extremely unbalanced samples in each category. Their evaluation of the impact matrices demonstrated that the polarization difference (PD), brightness temperature (Tc) and surface emissivity at high-frequency channels dominate the decision process, which is consistent with the physical understanding of polarized microwave radiative transfer over different surface types, as well as in snow and liquid clouds with different microphysical properties.

<u>Machine Learning for Nowcasting Precipitation:</u> Ehsani et al. (2022) developed two approaches (referred to as NowCasting-nets) that use recurrent and convolutional deep neural network (DNN) structures to address precipitation nowcasting. They trained a total of five models using IMERG precipitation data over the Eastern contiguous United States (CONUS) and then tested against independent data for the Eastern and Western CONUS. The authors designed the models to provide forecasts with a lead time of up to 1.5 h, and investigated extending to 4.5 h using a feedback loop approach. Benchmarks included the random forest (RF) and linear regression (LR) machine learning (ML) methods, a persistence benchmark (BM) that uses the most recent observation as the forecast, and optical flow (OF). Testing with independent IMERG observations showed that the NowCasting-net models were superior, with the convolutional NowCasting-net (CNC)

achieving 42%, 24%, 18%, and 16% improvement on the test set mean squared error (MSE) over the BM, LR, RF, and OF models, respectively, for the Eastern CONUS.

Improved Gauge Undercatch Correction: While precipitation gauges are considered the gold standard for assessing precipitation around the world, gauges tend to underestimate the precipitation, and it tends to be worse for solid precipitation. Ehsani and Behrangi (2022) compared two popular gauge-undercatch correction factors (CFs): one utilizes a dynamic correction model and is used in the Global Precipitation Climatology Centre (GPCC) Monitoring product and the other one has fixed monthly climatologies. The authors showed that the annual precipitation estimate from gauges (with no correction) can be biased by ∼9.61% over the global land (excluding Antarctica), although it varied depending on the season (from ∼6.80% in boreal summer to more than 12.33% in boreal winter).

Updates to the Goddard CSH Algorithm: Tao et al. (2022) reported upgrades to the Goddard Convective-Stratiform Heating (CSH) algorithm, which is used to retrieve latent heating (LH) associated with clouds and cloud systems in support of TRMM and GPM. The CSH algorithm requires a cloud-resolving model (CRM) to simulate LH profiles to build look-up tables. This paper describes the current V06 CSH in comparison with the previous V05. The TRMM and GPM Combined radar-radiometer algorithm-derived surface rain rates and their associated precipitation properties are the input to the CSH. The CSH V06-retrieved regional LH profiles in the tropics and subtropics display the classic signatures of heating in the convective region and heating over cooling in the stratiform region. Because there is no direct measurement of LH structure, the authors examined the CSH V06 algorithm by comparing its vertically integrated heating (or equivalent surface rain rate) against the surface rain rate computed from the TRMM/GPM Combined algorithm. The CSH three-month and zonal mean equivalent surface rain rates are in good agreement with the Combined rain rates over the Inter-Tropical Convergence Zone, while CSH three-month and zonal mean equivalent surface rain rates are larger than the Combined rain rates over land in both the tropics and subtropics. CSH three-month mean equivalent surface rain rates also have local differences with the Combined rain rates that can be smoothed by area averaging. CSH equivalent surface rain rates have more light rain rates but less larger rates compared to the GPM Combined surface rain rates.

Evaluating and Developing Climate Models: Temperature and water vapor sounding retrievals continue to be used for evaluating and developing climate models. The GISS Earth System Model (ESM) was used as a testbed for simulating the impact of wildfire smoke plumes on mid-high latitude surface weather and short-timescale tropospheric thermodynamics. In the model, unique warming (in the middle-upper troposphere) and cooling (in the lowest portion of the troposphere) signatures were simulated, with surface cooling much more pronounced than NWP models had projected, and these were found to be realistic and observed in Suomi-NPP CLIMCAPS retrieval products (Field et al., 2023). Regarding tropical studies, temperature and water vapor retrievals from AIRS V7 (Standard L2) and AIRS single FOV products are progressively being used to determine why convective systems move in the direction they do, and whether that is governed by local small-scale thermodynamic perturbations in the tropics. This knowledge will continue to inform convective parameterization development in the next version of the GISS ESM.

Representation of Precipitation in Regional Models: Cui et al. (2023) utilized assimilation of satellite data from multiple sensors, including AIRS, AMSU and CrIS, into a regional model to improve the numerical simulation of diurnal precipitation over the Maritime Continent region.

Analysis of Lightning Data

Demonstrating the Novel Utility of Combined Spaceborne Lightning and Lidar Observations: In a first-of-its-kind combined analysis of global spaceborne lightning and cloud lidar observations, Lang and Bang (2022) analyzed data from the Lightning Imaging Sensor (LIS) and the Cloud-Aerosol Transport System (CATS). The results found that thunderstorm cloud-top heights (CTH) slope downward from the Equator toward the poles, similar to how the tropopause height also slopes downward. Additionally, lidar measurements of cloud properties, like CTH and the amount of ice in the cloud, were quantitatively related to lightning observations like flash rate. The lidar also was helpful in finding rare instances where ISS LIS accidentally detected glint from the sun on water, snow, etc. instead of lightning. The results demonstrate that lidar observations can provide insight into the global thunderstorm climatology, are realistically correlated with lightning characteristics such as flash rate despite the lack of deep penetration into thunderclouds, and enable new methods for quality control and validation of spaceborne optical lightning observations.

Understanding the Performance of Spaceborne Lightning Observations: Two recent studies have evaluated the performance of spaceborne lightning mappers. Zhang et al. (2023) compared the International Space Station Lightning Imaging Sensor (ISS LIS; 2017-present) to the same instrument on the Tropical Rainfall Measuring Mission (TRMM; 1998-2015). While TRMM LIS appeared to be slightly more sensitive, this may be related to ISS attitude variations that make the sensor footprint larger for ISS LIS. Meanwhile, Virts and Koshak (2023) used an advanced Monte Carlo technique to examine how the Geostationary Lightning Mapper (GLM) performance varies across its field of view. Since ground-based reference lightning networks can have limited coverage, particularly in oceanic regions, this needs to be taken into account when assessing the overall performance of GLM.

Investigations into Lightning-initiated Wildfires: Lybrand (2023) and Vant-Hull and Koshak (2023) analyzed wildfires caused by lightning, in order to improve our understanding of why some weather events cause wildfires and others don’t, and whether some types of lightning are more likely to cause fires. Lybrand (2023) compared two potential wildfire outbreak days in California during August 2020. While both events had similar weather conducive to wildfire initiation and spread, this only occurred on one of the days, and aerosol loading from prior fires may have played a factor in inhibiting lightning on the inactive day. These results suggest there is potential utility in considering aerosol concentration and depth while forecasting fire potential. Meanwhile, Vant-Hull and Koshak (2023) found that lightning density from wildfire-parent storms peaks near the wildfire ignition point, and that positive lightning flashes could be up to 60 times more efficient at igniting fires than negative flashes.

Unprecedented Lightning and Gamma-rays during the 2022 Tonga Volcanic Eruption: Briggs et al. (2022) and Van Eaton et al. (2022) used satellite- and ground-based lightning observations to characterize the evolution of the enormous plume produced by the 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption. The analysis demonstrated that the plume induced massive gravity waves as it shot up to 58 km MSL. The eruption of Tonga also likely produced the highest flash rates ever recorded (~2600 flashes per minute) as well as a terrestrial gamma-ray flash (TGF).

Improving the Atmospheric Models and Prediction

Observing System Simulation Experiments, Demonstrator Instrument for Total Atmospheric Column Oxygen Content: A demonstrator instrument, the Microwave Barometric Radar and Sounder (MBARS) has been proposed for measuring surface air pressure over the marine surface with a combined active-passive scanning multichannel differential absorption radar to provide an estimate of the total atmospheric column oxygen content. Prive et al. (2023) have conducted a proof-of-concept study to evaluate the potential impact of spaceborne surface pressure data on numerical weather prediction using the GMAO global OSSE framework. This OSSE framework employs NASA’s GEOS model and the hybrid 4D-EnVar GSI data assimilation system. Multiple flight and scanning configurations of potential spaceborne orbits were examined. Swath-width and observation spacing for the surface pressure data were varied to explore a range of sampling strategies. For wider swaths, the addition of the additional surface pressures reduces the root-mean-square surface pressure analysis error by as much as 20% over some ocean regions. Adjoint-based estimates of observation impact indicate impacts on the Pacific Ocean basin boundary layer 24-h forecast temperatures for spaceborne surface pressures that are on par with rawinsondes and aircraft and greater impacts than the current network of ships and buoys. The largest forecast impacts are found in the Southern Hemisphere extratropics.

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<u>Section 1</u> Atmospheric Composition Focus Area

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Section 3 Climate Variability and Change Focus Area

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Section 5 Water and energy Cycle Focus Area

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Section 6 Weather and Atmospheric Dynamics Focus Area

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