EARTH SCIENCE DIVISION

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

Section 1.1.8.1 Atmospheric Composition Focus Area

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

To demonstrate progress in characterizing the behavior of the Earth system, including its various components and the naturally-occurring and human-induced forcings that act upon it, ACFA sponsored research in FY2022 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) understand the emissions of greenhouse gases such as CO_2, methane (CH_4) and nitrous oxide (N_2O) that persist in the atmospheric on timescales of a decade to centuries with studies using data from the NASA OCO-2 and OCO-3 missions as well as from suborbital platforms and ground-based networks

(d) use NASA's portfolio of space-based instruments (OMI and MLS on Aura) 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.

Finally, ACFA researchers this past year have made important contributions to understanding the growing impacts of smoke from wildfires, both on air quality near the surface as well as in the free troposphere and stratosphere where it can impact not only Earth's radiation balance but also the chemistry of ozone. This work is summarized in subsections B and D below.

A. 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. These span ongoing development of aerosol and cloud retrievals and products, aerosols and cloud radiative effects, and smoke layers and the properties of particles produced by wildfires. Summarized in this section are 17 papers in this topic area out of more than five dozen published or in review this past year.

Aerosol retrievals and observations

Kahn et al. (2022) summarized the utility of the more than two-decade record from the Multi-angle Imaging SpectroRadiometer (MISR) for retrieval of aerosol optical depth and particle properties; smoke, dust, and volcanic aerosol plume heights; and near-surface particulate matter (PM) concentrations. Applications to aerosol transport and radiative forcing, climate-related process studies, and air quality/human health are highlighted, with example illustrations of MISR's sensitivity to particle type, spatial and temporal trends in PM2.5 sulfate and elemental carbon over California, and downwind smoke plume height and particle property evolution for the 2013 Government Flats Fire in Oregon.

Absorbing aerosols in the troposphere produce complex effects on UV radiances affecting estimation of ozone vertical profiles and total columns. *Jethva et al.* (2022) used radiative transfer model results with UV-absorbing carbonaceous smoke and mineral dust over a wide range of aerosol conditions to develop a new physics-based correction for absorbing aerosols. The new correction does not depend on specifics of the retrieval algorithms and thus can be applied to derive ozone from any UV sensor (*e.g.,* SBUV, OMI, OMPS, TOMS, TROPOMI) regardless of the algorithm's type and its aerosol sensitivity.

Schlosser et al. (2022) propose a simple method to derive vertically resolved aerosol particle number concentration (N_a) using combined polarimetric and lidar remote sensing observations. Comparison of the resulting lidar + polarimeter vertically resolved N_a product to *in situ* N_a data collected by airborne instruments during the NASA Aerosol Cloud Meteorology Interactions Over the western Atlantic Experiment (ACTIVATE). Their findings suggest that the error in the polarimeter-only column-averaged N_a and the lidar + polarimeter vertically resolved N_a are of similar magnitude and represent a significant improvement upon current remote sensing estimates of N_a.

Hilaro et al. (2021) leverage aerosol data from multiple airborne and surface-based field campaigns encompassing diverse environmental conditions to calculate statistics of the oxalate-sulfate mass ratio (median: 0.0217; 95% confidence interval: 0.0154–0.0296; R = 0.76; N = 2,948). Ground-based measurements of the oxalate-sulfate ratio fall within our 95% confidence interval, suggesting the range is robust within the mixed layer for the sub-micrometer particle size range. They demonstrate that dust and biomass burning emissions can separately bias this ratio toward higher values by at least one order of magnitude. In the absence of these confounding factors, the 95% confidence interval of the ratio may be used to estimate the relative extent of aqueous processing by comparing inferred oxalate concentrations between air masses, with the assumption that sulfate primarily originates from aqueous processing.

Sinyuk et al. (2022) provide the scientific underpinning of the Aerosol Robtic Network (AERONET) aerosol retrieval algorithm for expanded aerosol absorption products that will be implemented under AERONET's version 4 processing. The Version 3 aerosol retrieval algorithm imposed strong smoothness constraints on the imaginary part of refractive index that were tuned to black carbon (BC)-containing aerosols. The version 4 relaxed constraints will accommodate inversion of spectral absorption by different aerosol types without suppressing its natural variability. It will enable differentiation between brown carbon (BrC)- and BC- containing aerosol as well as characterize their mixtures.

Passive satellite observations play an important role in monitoring global aerosol properties, and the newest advanced baseline imagers (ABI) onboard the geostationary operational environmental satellites (GOES-R series) provide new capabilities. **Bian et al.** (2021) demonstrate that simultaneous dual-view observations with the operational ABIs on GOES-East and GOES-West throughout the day lead to a huge variety of scattering angles that provide constraints on the aerosol phase function. They reconstruct the aerosol phase function for a dust event in the Gulf of Mexico during 2019 and find that the aerosol optical depth retrievals from the two satellites become self-consistent and agree well with surface-based optical depth estimates.

Using airborne HSRL-2 measurements acquired in 2016 during the NASA ObseRvations of Aerosols above CLouds and their intEractionS (ORACLES) mission **Harshvardhan et al.** (2022) **s**tudy the evolution of biomass burning aerosol distributions and properties over the southeastern Atlantic Ocean. In the 3-5 km altitude range, 95% of the aerosol extinction was contributed by particles in the 0.05-0.50 µm radius size range, with the aerosol in this size range having an average effective radius of 0.16 µm. There is very little day to day variation in these properties. Furthermore, these measurements indicated that there was often a distinct gap between the bottom of the aerosol layer and cloud tops at the selected locations.

Boland and Diner (2021) summarize the technical elements and scientific motivation for the Multi-Angle Imager for Aerosols (MAIA) mission – NASA's first competitively selected investigation aimed specifically at societal benefit. MAIA brings remote sensing and epidemiological specialists together to explore associations between PM speciation and human health.

Dust speciation information is an important input to constrain direct radiative forcing of mineral dust in climate models and thus is of considerable interest to the air quality community. **Go et al. (2022)** developed an algorithm to derive column volume and mass concentrations of hematite and goethite – the main absorbers in mineral dust. Mass concentrations from the Earth Polychromatic Camera (EPIC) on board the Deep Space Climate Observatory (DSCOVR) retrieved with the Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm show very good agreement with *in situ* soil samples collected over major world dust source regions. The MAIAC EPIC data also show a significant seasonal variability driven by the regional weather patterns.

Aerosol particles act as cloud condensation nuclei (CCN) and initiate the formation of cloud droplets. Retrieval of CCN concentrations from passive sensors such as the Moderate Resolution Imaging Spectrometer (MODIS) are uncertain and represent a column-average value, rather than the CCN concentration near cloud base where the CCN directly impacts cloud properties. **Choudhury and Tesche** (2022) present an algorithm to estimate vertically resolved cloud condensation nuclei (CCN) concentrations from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) profile data. Applied to the CALIOP dataset, this algorithm is capable of producing the first observation-based 3-d global climatology of CCN, which will be highly beneficial for studies of aerosol impacts on boundary layer clouds and evaluations of aerosol-cloud interactions simulated in climate models.

Desert dust represents an important source of ice nucleating particles (INP) and impact Earth's radiation budget by modulating the reflectivity of ice clouds. However, observing tenuous dust layers in the upper troposphere at the altitudes where ice clouds occur is difficult. Dust detection and retrieval algorithms developed by **Yang et al.** (2022) are more sensitive to dust in the nighttime upper troposphere than the standard CALIOP algorithms. They apply combined profiles derived with their new algorithms with modeling to study dust transport patterns, identify source regions, and study the mechanisms responsible for lifting dust from the surface to the upper troposphere. Their results are an important step in quantifying INP and are a unique resource for validating the performance of climate models.

Aerosols, radiative forcing and cloud feedbacks

Loeb et al. (2022) use satellite, reanalysis, and ocean *in situ* data to evaluate regional, hemispheric and global mean trends in Earth's energy fluxes during the first 20 years of the twenty-first century. Regional trends in net top-of-atmosphere (TOA) radiation from the Clouds and the Earth's Radiant Energy System (CERES), ECMWF Reanalysis 5 (ERA5), and a model similar to ERA5 with prescribed sea surface temperature (SST) and sea ice differ markedly, particularly over the eastern Pacific Ocean, where CERES observes large positive trends. Hemispheric and global mean net TOA flux trends for the two reanalyses are smaller than CERES, and their climatological means are half those of CERES in the southern hemisphere (SH) and more than nine times larger in the northern hemisphere (NH). Results from this paper highlight a central role for well-calibrated satellite observations in establishing trend patterns in nature.

Travel restrictions in the wake of the COVID-19 pandemic resulted in an unprecedented decrease of 73% in global flight mileage in April–May 2020 compared to 2019. **Zhu et al. (2022)** examine CALIPSO satellite observations and find a significant increase in ice crystal number concentrations (N_i) in cirrus clouds in the mid-latitudes of the Northern Hemisphere, which they attribute to an increase in homogeneous freezing when soot from aircraft emissions is reduced. A relatively small positive global average radiative effect of 21 mW m^{-2} is estimated if a decrease in aircraft traffic continues, with an average of up to 64 mW m^{-2} over the area where aviation is most active. They infer from this analysis that the worldwide adoption of biofuel blending in aircraft fuels that lead to smaller soot emissions could lead to a significant change in the microphysical properties of cirrus clouds but a rather small positive radiative effect.

Yuan et al. (2022) combine deep learning models and global NASA's Aqua MODIS daytime satellite observations to automatically identify ship-tracks at unprecedented scales. They find a reduction in ship track-identified cloud cover over the Aqua era. They attribute this to international fuel regulations mandating a reduction in sulfur content in designated Emission Control Areas that by 2020 had reduced ship track frequency in 2020 to its lowest level in recent decades across the globe. The fuel regulation reduces the aerosol indirect forcing from ship emissions by 37% or between 0.02 and 0.22 Wm^{-2} given its current estimates. The study quantifies indirect effects using the MODIS standard cloud products (MYD06), specifically cloud optical thickness and cloud effective particle radius.

Theoretical considerations predict that high-altitude tropical clouds should rise with global warming, a feedback that amplifies the warming. Previous studies used multi-satellite products to report that tropical clouds are getting higher, but there were large uncertainties likely caused by combining data from different satellites. **Richardson et al.** (2022) use MODIS Terra and Aqua cloud top property datasets to quantify gridded and zonal regional cloud top height changes during the 2002-2021time period. While the changes observed are small (e.g., tropical changes of about +70 m/decade for both Terra and Aqua MODIS), the results are reasonably close to cloud top height changes reported by atmospheric models (Atmospheric Model Intercomparison Project [AMIP] runs with prescribed sea surface temperature and sea ice) over a 3-decade or longer time period.

Multi-angle polarimetry and aerosol retrievals for the PACE mission

NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, scheduled to launch in January 2024, will carry two multi-angle polarimeters (MAPs). The measurements from these sensors enable detailed characterization of aerosol microphysical and optical properties, including aerosol absorption, and have the potential to improve atmospheric correction in ocean color remote sensing. A key aspect for using such advanced remote sensing products is having valid and robust pixel-level estimates of their uncertainty. In **Gao et al.** (2022) these uncertainty estimates are validated using a flexible and fast Monte Carlo approach applied to both synthetic and airborne data sets. These results will facilitate the effective use of PACE aerosol retrieval products by a wide community of users immediately after launch.

Van Diedenhoven at al. (2022) develop a framework to infer volume water fraction, soluble fraction and dry size distributions of fine-mode aerosol from multi-angle, multi-spectral polarimetry retrievals of column-averaged ambient aerosol properties. These retrievals of fine-mode water volume fraction and soluble fraction may be used for the evaluation of water uptake in atmospheric models. Furthermore, the framework allows the variation in the concentration of fine-mode aerosol larger than a specific dry radius limit to be estimated, which can be used as a proxy for the variation in cloud condensation nucleus concentrations. This framework may be applied to multi-angle, multi-spectral satellite data expected to be available in the near future from the PACE mission.

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

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. In this section we summarize 16 out of close to five dozen papers this year that are related to measurements of trace gases and aerosols that affect air quality, the effects of biomass burning, impacts of COVID-19 shutdowns, and global changes in tropospheric ozone.

Precursor emissions, chemistry and regional air quality

Kotsakis et al. (2022) use the ground-based Pandora sun-sky spectrometer systems along with other remote and *in situ* measurements to evaluate the sensitivity of ozone production to the exposure of air masses to water. The analysis uses airmass trajectories to quantify the exposure of air to the water interface and measurements from Pandora and ozone lidar instruments during the Ozone Water-Land Environmental Transition Study Phase 2 (OWLETS-2) campaign. to quantify the effect on chemistry in the Chesapeake Bay. The results show a distinct altitude dependence in the production of ozone that is attributable to the impact of the air-water interface. This result underscores the need for high resolution models and measurements to capture these effects in the complex environments of coastal regions.

Tao et al.(2022, in review) investigate how ozone precursors change between polluted and non-polluted days using remote sensing of nitrogen dioxide (NO_2) and formaldehyde (HCHO) from Sentinel-5P TROPOMI and GEO-CAPE airborne simulator observations in New York City and Baltimore. On days that exceed the ozone pollution standards, both NO_2 and HCHO are higher in New York City with increases in HCHO resulting in more sensitivity of ozone formation to NO_x emissions, which were also found to be larger on high ozone days. This result demonstrates the need for continued NO_x emission reductions in the NYC and Baltimore areas to achieve ozone pollution standards set by the US EPA.

Through its role as a precursor for fine particulate matter, atmospheric ammonia (NH_3) can have negative impacts on both human health and ecosystem function. **He et al.** (2021) utilize the long-term AIRS record to quantify spatiotemporal changes in atmospheric NH_3 between 2002 and 2016, finding strong increases in NH_3 across the U.S., with the highest increases observed in the Midwest, followed by the Mid-South and West regions. Agriculture being a major source of atmospheric NH_3, the study also examines empirical relationships with fertilizer application, livestock manure production, and climate factors (precipitation and temperature). The results could help to provide a basis for U.S. policy makers in developing mitigation strategies for agricultural NH_3 emissions under future climate change scenarios.

Chen et al. (2021) use measurements of ammonia from AIRS and IASI together with measurements of sulfur dioxide and nitrogen dioxide from OMI to constrain top-down estimates of reactive nitrogen emissions over China over the 2005-2015 time period and then quantify their contributions to air pollution from $PM_{2.5}$. The results show that while interannual $PM_{2.5}$ changes due to NH_3 emission changes are relatively small compared to the changes associated with reductions in NO_x emissions, further control of agricultural NH_3 emissions can still be effective for the mitigation of $PM_{2.5}$ pollution in eastern China.

Isoprene is a naturally occurring trace gas emitted primarily from the leaves of woody plants. Isoprene has important impacts on both air quality and climate; however, these impacts are difficult to assess and predict given large uncertainties in its sources and atmospheric chemistry. Space-based measurements can help to address these uncertainties. **Wells et al.** (2022) show daily, global isoprene distributions from 2012 to 2020. Results over North America and Amazonia highlight the processes controlling isoprene abundances and their variability over time.

Souri et al. (2022) present a comprehensive error characterization of satellite-based $HCHO/NO_2$ Tropospheric Column Ratios (FNRs) in predicting the near-surface ozone sensitivity. Errors from chemistry, column to planetary boundary layer (PBL) translation, spatial representation, and retrieval uncertainties are investigated in detail. They show that the satellite column retrieval error is the largest contributor to the total error (40-90%) in the FNRs, and suggest that continuing development in the retrieval algorithm and sensor design and calibration is essential to be able to advance the application of FNRs beyond a qualitative metric.

Biomass burning, plume chemistry, transport and impacts on air quality

Wilmot et al. (2022) develop a plume rise climatology of ~4.6 million smoke plumes occurring within the western US and western Canada during the months of August and September for the years 2003-2020. The model results were validated by comparisons with the MISR observational plume heights database. The findings indicate that current trends towards enhanced wildfire activity correspond to elevated wildfire plume-top heights and aerosol injection aloft for the majority of mountainous ecoregions across the western US. These results suggest a causal link between climate change and the increase in wildfire plume top heights and enhanced injection of aerosols above and within the boundary layer, leading to a growing risk of air quality degradation downwind of the fires.

Mardi et al. (2022) characterize biomass burning (BB) aerosol events over the U.S. East Coast and Bermuda over the western North Atlantic Ocean (WNAO) between 2005 and 2018 using a combination of AERONET observations, satellite data, and MERRA-2 analysis fields. They find BB days are present year-round with more in June–August (JJA) over the northern part of the East Coast, in contrast to more frequent events in March–May (MAM) over the southeast U.S. and Bermuda. BB source regions in MAM are southern Mexico and by the Yucatan, Central America, and the southeast U.S. JJA source regions are western parts of North America. Profiles of aerosol extinction suggest that BB particles can be found in the boundary layer and into the upper troposphere with the potential to interact with clouds.

Fine-ash particles from BB events have not yet been explicitly considered as a major aerosol component either in field observations or climate models. **Adachi et al. (**2022) measure BB aerosol samples using transmission electron microscopy (TEM) and ion chromatography during the Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) campaign. They show that significant amounts of fine ash-bearing particles are transported >100 km from their fire sources. Environmental chamber experiments suggest that they can act as cloud condensation and ice nuclei.

Buchholz et al. (2022) use the long time-record of Measurement of Pollution in the Troposphere (MOPITT) carbon monoxide observations to analyze changes in the seasonal pattern of pollution over North America. They show that increasing western wildfires are altering the seasonal pattern of air pollution and causing a spike in unhealthy pollutants in August. The smoke is undermining clean air gains and poses potential risks to the health of millions of people.

Peatlands are an important economic asset in Indonesia, given their potential use for agricultural development. However, drainage in agricultural conversion dries out the land and increases the propensity for wildfire spread**. Hein et al.** (2022)) examine the long-long-term effects on mortality and morbidity of peatland fires in Sumatra and Kalimantan, using monthly estimates of air pollution concentrations derived by relating MISR- and MODIS-derived aerosol optical depths to PM2.5 concentrations with the GEOS-Chem chemical transport model. They found that 33,100 adults and 2,900 infants in Sumatra and Kalimantan die prematurely each year from exposure to $PM_{2.5}$ pollution from peatland fires. On average, an additional 4,390 respiratory hospital admissions, 635 thousand severe asthma symptom days among asthmatic children, and 8.9 million lost workdays were identified.

COVID-19 impacts on tropospheric composition and air quality

Chang et al. (2022) use selected Network for Detection of Atmospheric Composition Change (NDACC) ozonesonde and lidar observations to better quantify regional scale ozone anomalies throughout the depth of the troposphere and stratosphere by combining multiple sources of vertical profile records. They find that 2020 is the only year in which both Europe and North America exhibit coincident and profound negative anomalies since the benchmark year of 1994. The likely explanation is the decrease in ozone precursor emissions due to the COVID-19 economic downturn. Including those large negative anomalies in 2020, the positive 1994–2019 ozone trends above Europe and western North America are diminished.

With modeling and extensive air quality (AQ) and greenhouse gas (GHG) satellite observations, **Laughner et al.** (2021) show a sharp difference in the response of GHG and AQ atmospheric concentrations to COVID-19 emissions changes, due in large part to their different lifetimes. Despite dramatic declines in vehicular emissions, the atmospheric growth rates of greenhouse gases were not slowed, in part due to decreased ocean uptake of CO_2 and a likely increase in CH_4 lifetime from reduced NO_x emissions. The response of O_3 to decreased NO_x emissions showed significant spatial and temporal variability, due to differing chemical regimes around the world. Finally, the overall response of atmospheric composition to emissions changes is heavily modulated by factors including carbon-cycle feedbacks to CH_4 and CO_2, background pollutant levels, the timing and location of emissions changes, and climate feedbacks on air quality, such as wildfires and the ozone climate penalty.

Field et al. (2021) use the long-term Aqua AIRS record of carbon monoxide, together with Aqua MODIS aerosol optical depth and records of sulfur dioxide and nitrogen dioxide from the Ozone Monitoring Instrument (OMI) on Aura, to understand how COVID-19 lockdowns impacted atmospheric composition over eastern China. They find that all of these quantities were lower during the lockdown window than the background mean from the surrounding time period. The study also emphasizes the sensitivity of estimates of COVID-related impacts to the choice of background period and the prevailing trends. These results illustrate the value of the long-term nature of the Aqua and Aura satellite records.

Changes in tropospheric ozone

Wang et al. (2022) used ozone observations from ozonesonde stations and In-Service Aircraft for a Global Observing System (IAGOS) profiles, coupled with a GEOS-Chem model simulation to quantify and attribute the causes of observed tropospheric ozone trends from 1995-2017. Positive ozone trends derived from the observations are particularly strong in the tropical and subtropical lower troposphere with 2.8 to 10.6 ppbv $decade^{-1}$ increases. The GEOS-Chem simulation reproduces the observed pattern in ozone trends but underestimates the strength of the positive trends. Much of the observed tropospheric ozone increases and associated positive radiative forcing effects are attributed to the recent shift in ozone precursor emissions toward tropical latitudes and an increased role of aircraft emissions.

Ziemke et al. (2022) examine NASA satellite data from Suomi National Polar-Orbiting Partner (SNPP) Ozone Mapping and Profiler Suite (OMPS), Aura OMI and Microwave Limb Sounder (MLS), and DSCOVR EPIC and find anomalous decreases in tropospheric column ozone (indicative mostly of free tropospheric ozone) of ~5-10% throughout the NH in spring-summer months of 2021 comparable to those observed in 2020. The NH ozone amounts in 2020 and 2021 were the lowest on record for the 2005-2021 time period considered in this study. They conclude that decreases in pollutants due to reduced human activities including lockdowns during COVID-19 likely led to most of these decreases measured in free tropospheric ozone.

C. GHG sources, sinks, fluxes and trends

ACFA supports research into the emissions and fluxes of CO_2, methane (CH_4) and nitrous oxide (N_2O) involving data from the NASA OCO-2 and OCO. These observations also underpin observations and modeling of the carbon cycle by NASA-supported researchers. Thirteen of the most significant papers from the last year are summarized here.

CO2 emissions

Byrne et al. (2022) developed a "top-down" carbon budget of CO_2 emissions and removals for countries to support the global stocktake of the Paris Agreement. The CO_2 budgets were created from an ensemble of top-down estimates of the net surface-atmosphere CO_2 flux produced by the OCO-2 science team, in combination with fossil fuel emissions and lateral carbon fluxes (due to wood trade, crop trade, and rivers) from bottom-up models. Accounting for both anthropogenic emissions and changes in natural carbon storage, the products are expected to help inform inventory development and identify strategies to produce operational top-down carbon cycle products that can be used to quantify the impact of emission reduction activities.

Chevallier et al. (2022) use the multi-year archive of the Orbiting Carbon Observatory-2 (OCO-2) and the Orbiting Carbon Observatory-3 (OCO-3) platforms to retrieve large fossil fuel CO_2 emissions over the entire globe with emission retrievals are based on a simple emission retrieval scheme. These they compare to results from a global gridded and hourly inventory. They describe how emission retrievals from both OCO missions explain more than one third of the inventory variance at the corresponding cells and hours. More importantly, emission trends and changes can be robustly calculated but only as the length of the data record grows.

Taylor et al. (2022) document in detail the Greenhouse Gases Observing Satellite (GOSAT) XCO2 product retrieved using version 9 of the ACOS algorithm (ACOS-V9). The GOSAT XCO2 product is the longest running satellite CO_2 dataset; thus, it is highly useful for studying how the carbon cycle changed over the past decade. This study shows the spatiotemporal coverage achieved by V9-ACOS and validates it against ground-based columns from the Total Carbon Column Observing Network (TCCON) and a multi-model ensemble. Also included is a comparison to OCO-2 XCO2 data for their overlapping period. These validation and comparison results will help data users understand the accuracy of this data, as well as any biases against other sources of CO_2 data that must be accounted for when trying to combine the GOSAT data with other sources.

Using quality control thresholds tailored to OCO-2 retrievals over boreal forest regions, **Jacobs et al.** (2021) analyze OCO-2 and TCCON XCO2 data to constrain the seasonal cycle amplitude and phase over northern high latitudes. They find that the spatial patterns of seasonal cycle amplitude and the timing of the summer drawdown agree well with corresponding estimates from two models, but that the Asian boreal forest is anomalous with the largest amplitude and earliest seasonal drawdown. Modeled land contact tracers suggest that accumulated CO_2 exchanges during atmospheric transport play a major role in shaping carbon dioxide seasonality in northern high-latitude regions.

Methane emissions and fluxes

Barton-Grimely et al. (2022) report on measurements by the High Altitude Lidar Observatory (HALO) methane lidar on board the NASA C-130 during the summer 2019 ACT-America EVS-2 campaign. HALO provided the first-ever observations of co-located methane columns and quantitative aerosol distributions, allowing for identification of biogenic and anthropogenic methane sources over a wide range of ecosystems and urban settings. The results demonstrate the accuracy and sensitivity of the HALO instrument over a wide dynamic range, encompassing strong, localized oil and gas signatures to more distributed biogenic emissions from agriculture and wetlands in the Mississippi River Delta.

Worden et al. (2022) quantify methane fluxes based on total column CH_4 data from GOSAT and GEOS-Chem. Projecting these fluxes to country emissions, they find that agricultural and waste emissions are ∼263 Tg CH_4 yr^{-1}, anthropogenic fossil emissions are ∼82 Tg CH_4 yr^{-1}, and natural wetland/aquatic emissions are ∼180 Tg CH_4 yr^{-1}, consistent with previous inversions based on GOSAT data and the GEOS-Chem model. Their results suggest remote-sensing-based estimates of methane emissions can be substantially different (although within uncertainty) than bottom-up inventories, isotopic evidence, or estimates based on sparse *in situ* data, indicating a need for further studies reconciling these different approaches for quantifying the methane budget.

Lavaux et al. (2022) use TROPOMI data to detect methane emissions from the largest point sources in global oil and gas basins. This small number of sources is responsible for 8-12% of global CH_4 emissions. Other papers have recently shown that the operational land surface imagers Sentinel-2 and Landsat also have sensitivity to super-emitters and ultra-emitters, thus opening the possibility to retroactively create a long-term time-series of emissions from this source category. This work complements Worden et al.'s total column emissions estimates, providing a multi-pronged approach to quantifying global CH_4 emissions and managing their mitigation.

Lu et al. (2022) quantify methane emissions and their 2010–2017 trends by sector in the contiguous United States (CONUS), Canada, and Mexico by inverse analysis of *in situ* (GLOBALVIEWplus CH4ObsPack) and satellite (GOSAT) atmospheric methane observations. They find that GOSAT and *in situ* observations are largely consistent and complementary in the optimization of methane emissions for North America. Mean 2010–2017 anthropogenic emissions from their base GOSAT+ *in situ* inversion are 36.9 Tg yr^{-1} for CONUS, 5.3 Tg yr^{-1} for Canada, and 6.0 Tg yr^{-1} for Mexico. Total CONUS anthropogenic emissions peaked in 2014, in contrast to the EPA report of a steady decreasing trend over 2010–2017. This reflects offsetting effects of increasing emissions from the oil and landfill sectors, decreasing emissions from the gas sector, and flat emissions from the livestock and coal sectors.

Scarpelli et al. (2022) present an updated version of the Global Fuel Exploitation Inventory (GFEI) for methane emissions and evaluate it with results from global inversions of atmospheric methane observations from satellite (GOSAT) and *in situ* platforms (GLOBALVIEWplus). Global gas emissions in GFEI v2 show little net change from 2010 to 2019 while oil emissions decrease and coal emissions slightly increase. Global emissions from the oil, gas, and coal sectors in GFEI v2 (26, 22, and 33 Tg yr^{-1} , respectively in 2019) are lower than the EDGAR v6 and lower than the IEA inventory for oil and gas. The updated GFEI v2 provides a platform for evaluation of national emission inventories reported to the UN Framework Convention for Climate Change (UNFCCC) due to the improved coverage and spatial resolution of the newer generation of satellite instruments such as the Tropopsheric Monitoring Instrument (TROPOMI) on Sentinel 5 Precursor. It will be especially beneficial in regions such as Russia where current inversion systems have limited sensitivity.

China's anthropogenic methane emissions are the largest of any country in the world. **Sheng et al.** (2021) suggest that recent policies aimed at reducing emissions of methane due to coal production in China after 2010 had been largely ineffective. While the upward trend in China's methane emissions has slowed due to a decline in coal production, coal mine methane emissions have not declined as rapidly as production. Thus there may be substantial fugitive emissions from abandoned mines that have previously been overlooked. Similarly, emissions over rice-growing and aquaculture-farming regions show a positive trend despite reports of shrinking rice paddy areas, implying potentially significant emissions from new aquaculture activities, which are thought to be primarily located on converted rice paddies.

Validation of Nitrous Oxide satellite measurements

Vandenbussche et al. (2022) are the first to use the TCCON X_{N2O} data product for satellite validation, specifically the Infrared Atmospheric Sounding Interferometer (IASI) N_2O product (NOPIR) with its potential for long-term global N_2O monitoring. They present a time series of ten years (2011–2020) of IASI N_2O profiles and integrated partial columns and its validation with collocated ground-based NDACC and TCCON data. They show good agreement with the NOPIR and ground-based measurements. They highlight the growing importance of high quality X_{N2O} measurements and motivates further study of the TCCON X_{N2O} product.

Wildfire impacts on the carbon cycle

Byrne et al. (2021) find that the 2019-2020 Australian wildfires released 113-236 TgC of CO_2 while drought and fire-induced anomalies in net ecosystem exchange (NEE) reduced growing season carbon uptake by an additional 19-52 TgC of CO_2. The net 2019-2020 carbon loss far exceeded interannual variations in net uptake over 2010-2019 estimated from top-down constraints and even exceeded Australia's annual fossil fuel emissions. This study demonstrates that space-based measurements (TROPOMI X_{CO}, OCO-2 X_{CO2}, MODIS-based gross primary production [GPP]) provide strong observational constraints on carbon flux anomalies from such extreme events. The results of this study have implications for the regional carbon budget of southeast Australia, with more frequent climate-change-driven heat and drought events increasing the frequency of fires and the recovery time of ecosystems, threatening the carbon stocks of the region.

COVID-19 impacts on greenhouse gas emissions

Weir et al (2022) use the GEOS/OCO-2 carbon monitoring system to show a 0.24- 0.48 ppm reduction of column CO_2 growth due to the COVID-19 restrictions in early 2020. Attribution of these small CO_2 signals to changes in anthropogenic emissions remains challenging as interannual variability in transport and biospheric carbon-climate teleconnections both drive concentration changes many times greater than the record-setting changes in regional anthropogenic emissions due to COVID-19. The ability to detect fossil fuel CO_2 emission changes in the midst of natural carbon cycle variability is a milestone toward the long-term goal of monitoring future emissions, especially given the planned increase in space-based observing capability.

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. The latter has come increasingly to involve research into the effects of smoke injections into the upper troposphere and lower stratosphere (UTLS) from pyroCumulonimbus in addition to the ash and SO_2 from volcanoes. We highlight in this section 14 out of 39 papers from the last year on the topics of ozone depleting substances, emissions and trends, UTLS aerosols, and measurements of upper atmosphere composition change.

Ozone recovery and trends

Kramorova et al. (2021) analyze the 2020 ozone hole using the NDACC South Pole ozonesonde record, MLS, SNPP OMPS and OMI ozone satellite profiles, and NASA MERRA-2 temperature data. The 2020 austral spring was marked by a lack of planetary wave activity that resulted in a cold and stable polar stratospheric vortex, creating favorable conditions for ozone depletion. The winter-to-summer circulation transition was delayed by several weeks leading to the longest-lived ozone hole in the observational record. Record low ozone values in late austral spring and early summer led to unusually high levels of ultraviolet (UV) radiation in the region south of 60°S.

Stone et al. (2021) show that the record sizes of the Antarctic ozone holes in 2015 and 2020 still adhere to a fundamental recovery metric: the later onset of early spring ozone depletion as chlorine and bromine diminishes. This behavior is also captured in the Whole Atmosphere Chemistry Climate Model (WACCM). They quantify observed recovery trends of the onset of the ozone hole and in the size of the September ozone hole, with good model agreement. Their results indicate that, due to dynamical phenomena, it is likely that large ozone holes will continue to occur intermittently in October–December, but ozone recovery will still be detectable through later onset and reduced size and depth of September ozone holes – metrics that are governed more by chemical processes.

Yook et al. (2022) found evidence in OMPS LP ozone and aerosol measurements to support the hypothesis that the 2020 and 2021 Antarctic ozone holes were influenced by two extraordinary events: the Australian wildfires of early 2020 and the eruption of La Soufriere in 2021. They argue that both ozone holes were associated with changes in Southern Hemisphere surface climate consistent with the established climate impacts of Antarctic ozone depletion. Together, the results provide suggestive evidence that injections of both wildfire smoke and volcanic emissions into the stratosphere can lead to hemispheric-scale changes in surface climate.

Emissions and trends in ozone depleting substances

Growing emissions of unregulated short-lived anthropogenic chlorocarbons are offsetting reductions in ozone-depleting substances mandated by the Montreal Protocol on Substances that Deplete the Ozone Layer. In that regard, **An et al.** (2021) report an average annual increase of 13% increase in emissions from China of the chlorocarbon dichloromethane (CH_2Cl_2), and this overall increase is of the same magnitude as the global emission rise of 354 (281−427) Gg yr⁻1 over the same period. If global CH_2Cl_2 emissions remain at 2019 levels, they could lead to a delay in Antarctic ozone recovery of around 5 years compared to a scenario with no CH_2Cl_2 emissions.

Pardo Cantos et al. (2022) build on several previous papers investigating NDACC Fourier Transform Infrared spectrometer (FTIR) retrievals and trends of CFCs and HCFCs to show the slowdown of the decrease in CFC-11 at two stations. This corroborates similar trend changes seen in AGAGE data records. This work prepares these retrievals for wider deployment to the network and for inverse modeling efforts complementing AGAGE in situ data.

Methyl bromide (CH_3Br) is a potent ozone-depleting substance (ODS) that has both natural and anthropogenic sources. CH_3Br has been used mainly for preplant soil fumigation, post-harvest grain and timber fumigation, and structural fumigation. **Choi et al.** (2022) analyze high-precision, *in situ* measurements of atmospheric mole fractions of CH_3Br obtained at the Gosan station on Jeju Island, South Korea, from 2008 to 2019. Over this period, background mole fractions declined from 8.5±0.8 ppt to 7.4±0.6 ppt. They estimate anthropogenic CH_3Br emissions from eastern China at an average of 4.1±1.3 Gg yr^{-1}, more than 2/3 higher than the bottom-up emission estimates reported to UNEP. These unreported anthropogenic emissions of CH_3Br are confined to eastern China and account for 30–40 % of anthropogenic global CH_3Br emissions.

Froidevaux et al. (2022) analyze Aura MLS monthly zonal mean time series of ClO and HOCl between 50° S and 50° N to estimate upper stratospheric trends in these chlorine species from 2005 through 2020. They compare these observations to those from the WACCM version 6 run under the specified dynamics configuration. The model daytime ClO trends versus latitude and pressure agree quite well with those from MLS. Both data and model results point to a faster trend in ClO than in HOCl. The decreasing trends in upper stratospheric ClO and HOCl provide additional confirmation of the effectiveness of the Montreal Protocol and its amendments, which have led to the early stages of an expected long-term ozone recovery from the effects of ozone-depleting substances.

Stratospheric composition observations

Livesey et al. (2021) have reprocessed data from the entire MLS mission, and preliminary comparisons to ACE-FTS v4.1 show a reduction of about 2 %–4 % per decade in the H_2O drifts. As a result, a statistically significant drift between MLS v5 H_2O and ACE-FTS observations is no longer seen. Additionally, drifts in comparisons of MLS v5 H_2O to frost point measurements are reduced compared with those in v4 but are still statistically significant. For N_2O, statistically, significant drifts remain between MLS v5 and ACE-FTS, although they are reduced to about half the magnitude of those seen for MLS v4.

Using all active NDACC stations**,** **Hannigan et al.** (2022) provide the most complete temporally- and vertically-resolved OCS dataset available for the lower free troposphere and lower stratosphere. As the largest non-volcanic source of sulfur to the stratosphere, OCS is critical to the stratospheric aerosol layer and for biospheric carbon cycling as a proxy for CO_2. Consequently, this dataset should find wide use in investigations of both active research areas. Multi-year non-linear trends are determined to be due to anthropogenic sources, and since 2017 trends are declining globally.

Stratospheric water vapor

Water vapor is an effective greenhouse gas. Human-induced climate change has led to warmer air in the troposphere, which consequently can hold more moisture, thus enhancing the greenhouse effect. Using satellite observations (MLS), balloon soundings (FPH) and model (ERA5) simulations, **Konopka et al.** (2022) find an increase in stratospheric water vapor (SWV) after 2000. This increase is stronger in the Northern than in the Southern Hemisphere, mainly during late winter and spring, and is in line with a warming of the tropical tropopause, the coldest region that separates the troposphere and stratosphere. Natural causes such as volcanic eruptions cannot completely explain this stratospheric moistening.

The eruption of the Hunga Tonga-Hunga-Ha'apai volcano in mid-January 2022 resulted in the lofting of aerosols and volcanic trace gases to altitudes never seen before in the stratosphere. **Millán et al.** (2022) show that the Aura MLS observed direct injection of water vapor over a wide vertical range, extending as high as 53 km. The amount of water vapor injected is also unprecedented, despite the fact that MLS, OMI, and other sensors show that the amount of SO_2 injected was less than that from other notable volcanos in the Aura record. The enhanced water vapor is spreading throughout the southern stratosphere and into the Northern Hemisphere and is expected to endure over several years. This eruption could impact climate not through surface cooling due to sulfate aerosols, but rather through surface warming due to the radiative forcing from the excess stratospheric H_2O.

Impacts of widlfires on the stratosphere

Aura MLS and other sensors have shown that multiple intense thunderstorms triggered by the catastrophic Australian fires in early January 2020 injected distinct plumes of highly polluted air into the stratosphere. As **Santee et al.** (2022) report, subsequent MLS observations reveal a deep depletion in HCl, the main stratospheric chlorine "reservoir" species, accompanied by a strong enhancement in ClO, the main form of ozone-destroying reactive chlorine. Maximum reductions in HCl (50%–60% below average) were observed in mid-2020, months after the fires. Reactions that convert chlorine from reservoir to reactive forms, like the ones that take place in the winter polar regions and lead to the Antarctic ozone hole, are known to also occur in the midlatitude lower stratosphere on the surfaces of cloud particles or volcanic aerosols, but evidence of such chlorine "activation" had never before been observed in association with smoke in the stratosphere. The MLS measurements indicate that abundant and widely dispersed smoke particles from the Australian fires facilitated the conversion of chlorine to reactive forms over a large portion of the Southern Hemisphere for several months. Although such a sustained and widespread enhancement in reactive chlorine in the midlatitudes is unmatched in the MLS record, it was still far weaker than that in the Antarctic ozone hole, inducing at most minor changes in ozone in the Southern Hemisphere midlatitude lower stratosphere.

Solomon et al. (2022) use Stratospheric Aerosol and Gas Experiment (SAGE) III/ISS NO_x and aerosol extinction data in an analysis of the impact of midlatitude wildfire smoke on stratospheric chemistry. They show important decreases in stratospheric NO_2 concentrations following major Australian 2019 through 2020 wildfires that injected large amount of smoke particles into the stratosphere (~12 km above sea level). They found that important chemistry can occur on the smoke particle surfaces, which in turn contributes to the midlatitude ozone depletion.

The findings of Solomon et al. are further corroborated by **Bognar et al.** (2022) who analyze O_3 trends in 1984- 2021 from a long-term data record that combines SAGE II and SAGE III/ISS data together with other satellite data. They show that mid-latitude lower stratospheric ozone continues to decrease, contrary to model predictions. In tandem, these two papers, with significant use of SAGE data, reveal that the recovery of stratospheric O_3 layer, key to the protection of life on Earth from biologically damaging ultraviolet radiation, is slowing down, in part due to the increase of large fires in recent decade. They suggest that the climate models should consider the impacts of large fires on stratospheric chemistry.

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

The 2022 campaign of the EVS-2 Dynamics and Chemistry of the Summer Stratosphere (DCOTSS) project took place in June and July with 12 research flights of the NASA ER-2 out of Salina, Kansas and NASA's Armstrong Flight Research center in Palmdale, California. Together with the previous year's deployment, DCOTSS has completed a total of 23 research flights observing the integrated effects of deep overshooting convective processes and the North American Monsoon Anticyclone (NAMA) under late summer conditions. The project successfully met the primary mission goal by sampling material injected from the tops of intense thunderstorms in the stratosphere and also characterized large-scale stratospheric background conditions. Data is publicly available from the NASA online data archive, and analysis and modeling are underway to understand the impact of these overshooting storms on the stratospheric environment.

The NASA WB-57 deployed in late July to Osan AFB, Korea for the Asian Summer Monsoon Chemical and Climate Impact Project (ACCLIP) campaign, which is jointly funded by NSF (for the G-V and associated researchers) and NASA (for WB-57 and associated researchers) with smaller contributions from NRL and NOAA. The campaign goals are to better characterize the Asian Monsoonal Circulation and associated outflow. This year the circulation and outflow has cooperated such that numerous flights have probed both the interior of the anticyclone and outflow. As of August 25h, the WB-57 has completed 14 research flights, 9 in close scientific coordination with the NCAR G-V aircraft. The campaign ends in early September.

The Atmospheric Composition Focus Area provides support to a number of ground-based observational networks, both domestic and worldwide, including AGAGE, NDACC, AERONET, MPLNet, SHADOZ, TCCON, the Pandonia Global Network (PGN), and TOLNet. All continue to be operational despite substantial challenges imposed on their operations from the COVID pandemic. The networks continue to monitor key atmospheric trace constituents and provide critical validation for satellite-based measurements.

F. International Activities

Committee on Earth Observation Satellites, Atmospheric Composition - Virtual Constellation

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. In 2022, the CEOS AC-VC team produced a draft white paper entitled "Monitoring Surface PM2.5: An International Constellation Approach to Enhancing the Role of Satellite Observations".

<u>Section 1.1.8.2</u> 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. 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 to 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 biome shifts in the pan-Arctic and marine community restructuring induced by environmental change, impacts of alterations in land use change related to agriculture and sustainability, and furthering the understanding of carbon cycling and sequestration in coastal and open ocean systems.

Ocean Biology and Biogeochemistry

Better understanding Blue Carbon ecosystems

Ocean and coastal ecosystems sequester and store significant amounts of "blue carbon." Coastal blue carbon ecosystems, such as mangroves, seagrasses, and tidal marshes, are the most efficient natural carbon sinks on Earth. Relative to the area they cover, wetlands play an outsized and significant role in the global carbon cycle and have great potential to sequester carbon and methane from the atmosphere. For example, Menendez et al. (2022) revealed the impacts of extreme and episodic precipitation events on the dissolved organic carbon (DOC) flux into and out of tidal wetlands in the Northeastern US; the authors found that episodic events, such as hurricanes, can export large quantities of DOC, far greater than previously published. DOC is an important part of the global carbon cycle. Campbell et al. (2022) highlighted that remote sensing is an essential tool for estimating the amount, spatial distribution, and change in carbon stocks within and across blue carbon ecosystems, especially in areas that are harder to reach. Remote carbon monitoring is also critical for reporting and verifying carbon stocks and change across the land-sea interface, and while carbon mapping in mangrove systems is relatively advanced, other blue carbon ecosystems, such as seagrasses, still pose challenges for accurately mapping their distribution and extent (Regnier et al., 2022). A way to compensate for the shortcomings of remote sensing in challenging blue carbon ecosystems like submerged aquatic vegetation is to utilize satellite data with ecosystem models to assess the ability of coastal seagrass meadows to sequester carbon; Lebrasse et al. (2022) successfully developed a semi-automated approach for using time series analysis of remote sensing observations in seagrass ecology, complementing remotely sensed time series analyses with ground monitoring efforts.

Untangling climate forcings and their consequences in aquatic environments

A significant portion of climate change is due to anthropogenic activities. The COVID19 pandemic provided an opportunity to untangle the effects of human activities from natural variability. For example, Bosse et al. (2021) examined the impact of human activities on water quality and harmful algal blooms (HABs) in Lake Erie and Lake Huron using nearly a decade of satellite and in situ water quality measurements. The authors were able to identify several anomalies, including reduced suspended sediments potentially linked with changes in anthropogenic and natural forcings.

The impact of climate change is already affecting mammals and higher trophic levels that depend on phytoplankton and net primary production (NPP), which is an important metric describing the carbon cycle and ocean health. Vernet et al. (2021) examined rates of annual NPP around Greenland, an area very sensitive to climate change, between 2008-2017 using numerical models and remote sensing. The authors demonstrated the use of numerical modeling in detecting phytoplankton growth in Greenland shelves, particularly underneath seasonal sea ice, which is an area that has data paucity and is changing at a rapid pace. Indeed, they found that sea ice modulates the timing of phytoplankton growth, and that changes in Arctic sea ice flux will have an impact on NPP rates. Changes in NPP have cascading effects on other life in and around the global ocean. For example, Sylvester et al. (2021) used satellite ocean color data combined with the predictive capabilities of an earth system model to explore the drivers of variability in chlorophyll and temperature in the Antarctic, specifically focusing their study on the cascading effects of this variability on the population dynamics of krill. They determined that krill growth is driven by the ratio of the natural to anthropogenic climate variability, with krill growth over the next 20 years being dominantly driven by the natural signal, with a shift to being driven by the anthropogenic signal in the 30 years that follow. However, krill and microscopic life within the ocean are not the only species facing and learning to adapt to climate change. Jenouvrier et al. (2022) applied the time of emergence theory to distinguish the impacts of anthropogenic climate change from natural climate variability on emperor penguins, a concept that has never been applied to population dynamics of wild species. Connecting the linkages between biological and ecological observations to the underlying physical and chemical processes that impact ecosystems further advances our scientific understanding of life that depends on and lives within the ocean. For example, Mojica et al. (2021) showed how phytoplankton division rates are impacted by light and demonstrated how those changes in division rate have a proportional impact on phytoplankton biomass, which is key to understanding phytoplankton activity during the North Atlantic springtime. Understanding these mechanistic drivers of change are important to make predictions of future marine ecosystem condition and health.

Multi-decade sustained in situ and satellite observations are critical to distinguish natural versus anthropogenic drivers of change. Combining these techniques can be particularly powerful to identify changing environmental conditions, like an uptick in the frequency of or an intensification in size or duration of marine heatwaves, and the corresponding impacts on aquatic environments, ecology, and fisheries. The Gulf of Maine is one of Earth's fastest-warming water bodies, driven by inflows of warm, salty water from the North Atlantic, with phytoplankton productivity decreasing 65% over 20 years (1998-2018) due to sustained warming and ocean circulation changes, and several events of intensely corrosive water across entire region have been observed during recent winter seasons, which negatively impacted shellfish and some shell-forming plankton species (Balch et al., 2022). These significant ecosystem changes will have negative impacts on the overall productivity of the higher trophic levels and fishery yields, which are important components of the "blue economy." McKee et al. (2022) also utilized in situ ocean observations from Bio-Argo profiling floats coupled with satellite observations to understand drivers of chlorophyll anomalies in the North Atlantic Ocean and how these depend on the underlying mesoscale physical processes. They found that indeed mesoscale physical dynamics are important in setting plankton distributions; however, to capture certain biophysical processes which satellites miss due to scale, the sampling rates of Bio-Argo floats may need to be increased, which may not be compatible with the Bio-Argo mission, which seeks to maximize the length of the time series of observations while conserving power and reducing the risk of biofouling.

Further developing and refining ocean color algorithms
The light signal emerging from water contains many dimensions of information, including both color and polarization. These properties of light can be measured by spectrometer and polarimeter instruments that NASA deploys onboard satellites, including the upcoming PACE mission, which is part of the Program of Record identified in the NASEM 2017 Decadal Survey. McClain et al. (2022) provides a succinct and informative history of ocean color remote sensing and the role that NASA has played over the past 40 years. Yet, there is more work to be done, even on historical data to be able to accurately detect seasonality and trends from the data record. For instance, Bisson et al. (2021) recently revealed that there is a seasonal bias in the SeaWiFS, MODIS, and VIIRS ocean color data, relative to other independent ocean data observations. Understanding and accounting for these biases is important to ensure the climate record remains reliable and trends clearly identifiable. Further work is underway to quantify and characterize uncertainties that remain in satellite ocean color retrievals to improve their accuracy, such as uncertainties related to molecular, or Rayleigh, scattering of light (Gilerson et al., 2022).

While understanding and characterizing heritage ocean color sensors is important to accurately measure and interpret climate signals, advanced algorithm development is also needed for the next generation of ocean color satellite missions, which will bring cutting edge hyperspectral and polarimetric remote sensing into the forefront of the field. This objective is aligned with the priorities discussed and recommendations identified in the NASEM 2017 Decadal Survey. The next generation of ocean color sensors, including PACE, SBG, and GLIMR, will be hyperspectral, and Kramer et al. (2022) developed a methodology for inferring phytoplankton community composition from hyperspectral remote sensing satellite data to model thirteen different pigments used by different phytoplankton communities. Similarly, Kastadinov et al. (2022 a,b) developed an algorithm to partition phytoplankton carbon by size class using remotely retrieved properties of the backscatter of light and extract information on particle size distributions. Being able to determine the type of phytoplankton community and amount of biomass and carbon each contains are important steps towards advancing our understanding of life and the carbon cycle in the upper ocean.

Hyperspectral ocean color retrievals are just one of the innovations that the PACE mission will offer; PACE, expected to launch in early 2024, will also fly with two polarimetric instruments that measure the polarization of light, which is important to advance our understanding of the atmosphere, clouds, aerosols, and characteristics about the ocean surface. In anticipation of these instruments, Koestner et al. (2021) developed a method to estimate suspended particulate matter (SPM) in coastal waters from polarization signals. Similarly, Montes et al. (2022a) developed a method for improving retrievals of inland and nearshore atmosphere affects that are necessary to then interpret the signals from the underlying water bodies. There are also multiple approaches recently developed to use ocean color remote sensing to better understand phytoplankton dynamics and physiology. Gorbunov and Falkowski (2022) showed that solar-induced fluorescence is the only signal that is emitted from the ocean and detectable from space that can be unambiguously ascribed to phytoplankton physiology, and consequently, they revealed that oceanic photosynthesis is only at 50% of its potential due to limitations on the amount of nutrients available to phytoplankton. These are all critical advances in the use of optics to study biogeochemical processes of the Earth’s oceans and to be able to measure changes and assess threats to ocean and ecosystem function and health.

Ocean color remote sensing techniques are also being refined to measure and detect ocean constituents beyond plankton and macroalgae; remote sensing of marine debris (including plastic) is one application where significant attention is being devoted. Hu et al. (2022) examined the feasibility of distinguishing floating materials like sea snot and debris from each other. The authors found that with the current spectral and spatial resolution it is still difficult to distinguish the two without *a priori* information. Techniques are also being developed to leverage the additional wealth of information that global, coastal, and geostationary hyperspectral data will provide to advance data quality control. Dierssen et al. (2022) developed a novel approach to use the apparent visible wavelength metric as a quantitative method for quality filtering hyperspectral retrievals, like the ones PACE, SBG, and GLIMR will collect. This method is backwards compatible too, with relevance to heritage ocean color sensors, like VIIRS and MODIS.

This past year has also seen a timely advance in capacity building and knowledge transfer regarding remote sensing and radiative transfer principles for future generations to continue to leverage and build upon the progress made in ocean color remote sensing. Korkin et al (2021) developed a step-by-step guide with accompanying software and open-source code on how to write and implement radiative transfer models in a practical sense, in contrast to the more theoretical approaches often published in the peer-reviewed literature. This builds towards NASA’s goal of open source and open science (OSSI) for a more inclusive community.

Terrestrial Ecology

Vulnerability and Resilience of Northern Ecosystems

High latitude regions contain some of the most rapidly changing and vulnerable ecosystems on Earth. The Arctic Boreal Vulnerability Experiment (ABoVE) was designed as a 9 to 10-year comprehensive airborne-and-field effort to characterize the rapidly changing Arctic boreal terrestrial environment. ABoVE’s focus was anticipated to gradually shift from the impacts of environmental change on ecosystem dynamics (Phase 1 to comprise the first 3-4 years of the Experiment) to better understanding of the impacts to ecosystem services and the societal response (Phase 2 to take place over the second 3-4 years of the Experiment). The current year falls during Phase 2, and it represents the mid-point of ABoVE as a whole. ABoVE has provided an enhanced understanding of how key ecological properties are changing across space and time, and how these changes impact the Earth system and society.

To further understand the extent to which a biome shift is already underway in the boreal forest biome - a major component of Earth's biosphere and climate system - Berner and Goetz (2022) evaluated early indicators of a boreal forest biome shift using four decades of moderate resolution (30 m) satellite observations and biogeoclimatic spatial datasets. They quantified interannual trends in annual maximum vegetation greenness using an ensemble of vegetation indices derived from Landsat observations in areas without signs of recent disturbance. They found vegetation greenness increased at 38% and 22% of sample sites from 1985 to 2019 and 2000 to 2019, whereas vegetation greenness decreased (browned) at 13% and 15% of sample sites during these respective periods. Greening was thus 3.0 and 1.5 times more common than browning and primarily occurred in cold sparsely treed areas with high soil nitrogen and moderate summer warming. Conversely, browning primarily occurred in the climatically warmest margins of both the boreal forest biome and major forest types (e.g., evergreen conifer forests), especially in densely treed areas where summers became warmer and drier. These macroecological trends are consistent with early stages of a boreal biome shift.

Using a Landsat time series, Macander et al. (2022) quantified change of multiple Plant Function Types (PFTs) over recent years in northern and central Alaska and northwestern Canada. They mapped a 35-year time-series (1985–2020) of top cover (TC), a continuous measure of plant abundance, for seven PFTs across a 1.77 × 106 km^2 study area, improving on previous methods of detecting vegetation change by modeling TC. The PFTs collectively included all vascular plants within the study area as well as light macrolichens, a nonvascular class of high importance to caribou management. They identified net increases in deciduous shrubs, evergreen shrubs, broadleaf trees, and conifer trees, and net decreases in graminoids and lichens over the full map area, with similar patterns across Arctic and boreal bioclimatic zones. Most net change occurred as succession or plant expansion within areas undisturbed by recent fire, though PFT TC change also clearly resulted from fire disturbance. These maps have important applications for assessment of surface energy budgets, permafrost changes, nutrient cycling, and wildlife management and movement analysis.

As part of ABoVE's international collaborations, Zhang et al. (2022) conducted modeling studies to show changes in the effect of warming on Northern Hemisphere summer gross primary productivity for 2001–2100. The correlation between summer gross primary productivity and temperature decreases in temperate and boreal regions by the late twenty-first century, generally becoming significantly negative before 2070 in regions <60° N, though Arctic gross primary productivity continues to increase with further summer warming. These findings indicate that vegetation productivity could be impaired by climate change in the twenty-first century, which could negatively impact the global land carbon sink.

The Surface Biology and Geology (SBG) study, identified as one of the five designated foundational observations in the NASEM 2017 Decadal Survey, released a number of studies in a special issue of JGR-Biogeosciences to advance imaging spectroscopy across a range of ecosystems. SBG is being proposed as a global imaging spectrometer spanning the visible to shortwave infrared (VSWIR) and a separate multi-spectral thermal infrared (TIR) radiometer. One such study (Nelson et al. 2022), lays the framework to advance ecological questions in the tundra with a satellite imaging spectroscopy mission, with a focus on the spectral complexity of tundra driven by composition, sensitivity to climate, and phenology.

Remote sensing of vegetation composition, structure, and function
Remotely sensed data can help us better understand the role that vegetation plays in the global carbon cycle, and remote sensing of vegetation composition, structure, and function are key to improving our understanding of terrestrial carbon and ecosystem feedbacks. One novel tool that is providing groundbreaking information related to vegetation composition, structure and function is the Global Ecosystem Dynamics Investigation (GEDI); GEDI is a spaceborne lidar mission that was specifically designed to retrieve vegetation structure within a novel, theoretical sampling design that explicitly quantifies biomass and its uncertainty across a variety of spatial scales. Dubayah et al. (2022) provide an overview of the GEDI mission and present estimates of mean biomass densities at 1 km resolution, as well as estimates aggregated to the national level for every country GEDI observes, and at the sub-national level for the United States. These data serve as a baseline for current biomass stocks and their future changes and point the way towards potential new powerful monitoring tools for biomass from space. Indeed, GEDI data are beginning to revolutionize mapping of forest structure and biomass at global scales. As an example of this, Duncanson et al., (2022) described a robust approach for mapping global forest biomass and uncertainty at a 1 km spatial resolution by leveraging a combination of simulated GEDI data derived from airborne lidar measurements and coincident field measurements of forest structure. GEDI data are also being used to map additional attributes of forest and shrubland structure. For example, Lang et al. (2022) used GEDI data to map forest height and uncertainty across the globe attaining an RMSE of 2.7 m a with low bias. Ilangakoon et al. (2022) used GEDI to demonstrate that soil, water, and elevation are controlling factors in functional diversity in drylands. In addition to measuring attributes of forest structure, GEDI data can be leveraged to map forest change through time, especially when combined with other remote sensing data sets that provide wall to wall measurements through time. As an example of this, Rishmawi et al. (2022) combined GEDI data with optical data from the VIIRS sensor to map changes in forest structure across the conterminous United States from 2013-2022. The products developed from this study were able to capture changes in forest structure associated with partial harvesting, wind damage, wildfires, and other environmental stresses.

GEDI data are also being leveraged to better understand tree species diversity, a component of forest vegetation composition. Tree species diversity varies greatly across the Earth, ranging from about one species per hectare in boreal forests at high latitudes, to several hundred species per hectare in tropical forests. Marselis et al. (2022) applied GEDI data along with environmental and biogeographical variables to explain global patterns in tree species richness. They found that forest structure information from GEDI explained 66% of the variation in global tree species richness in natural forests without a history of recent disturbance. Understanding and predicting variations in tree species diversity is important because of the ecosystem services it provides, such as productivity and carbon sequestration.

Another interesting tool being used to further the understanding of vegetation function is solar-induced chlorophyll fluorescence (SIF); SIF is a variable related to vegetation function and is a promising remotely sensed proxy for carbon uptake due to its strong relationship with gross primary productivity (GPP, ecosystem carbon assimilated during photosynthesis). However, the relationship between SIF and GPP can be difficult to assess at satellite scales due to complexities associated with spatial and temporal dynamics. Pierrat et al. (2022) investigated the diurnal and seasonal dynamics of the SIF-GPP relationship by leveraging continuous tower-based measurements of SIF, GPP, and common vegetation indices. They found that SIF outperformed other vegetation indices as a proxy for GPP at all temporal scales but, but there was a non-linear relationship between SIF and GPP at small temporal scales (a half-hourly resolution). In another SIF study, Yang et al. (2022) investigated the relationship between SIF and GPP across different light and seasonal environments. They found that SIF increased in response to light earlier in the year than did GPP. The light response of GPP had a positive temperature dependence in spring, and this dependency reversed in summer due to increased evaporative demand, while the light response of SIF was less temperature dependent. These results suggest that, in conifer forests, photosystems begin to activate in spring prior to when water becomes available for photosynthesis, thus offering the potential to improve carbon cycle models of coniferous ecosystems.

Land Cover and Land Use Change

Urbanization

Remotely sensed data have long been utilized to monitor the urban environment and quantify changes. While useful for specific studies, two-dimensional image-based approaches often lack vertical change, which would provide the three-dimensionality needed for more comprehensive analyses. A recent study by Mathew and Nghiem (2021) using light detection and ranging (lidar)-based modeling of the urban environment specifically focused on quantifying built-up volume and modeling its change within urban areas using multi-temporal data. They found that carbon budget calculations for an urban area without considering the vertical dimension may lead to gross errors. The chapter included a summary of recent advancements in incorporating spaceborne radar data (e.g. from satellite scatterometer), to monitor built-up volume free from the limitations of high cost, and small area coverage, and discussions of the physical basis and future extension of high-resolution data synergistically from multiple satellite synthetic aperture radars (SARs). These advancements in data fusion promise to significantly contribute to applications of satellite remote sensing for urbanization.

Agriculture and sustainability of social-environmental systems

Agricultural transitions often occur in response to changing market demands, and economic and social factors pressure agriculturalists out of traditional subsistence farming into commodity production. These changes in practice represent an essential component of land use and land cover change in countries across the world. One such example is the development of extensive dragon fruit plantations in southern Vietnam, which has radically transformed local agriculture in response to external market demands from China, Australia, Japan, and the United States. In addition to the expansion of dragon fruit farming, the Bình Thuận Province of southern Vietnam, now considered as the “Dragon Fruit Kingdom,” has also experienced rapid urbanization due to the tourism boom in the city are creating the conditions for a dual rural-urban hotspot where both city areas and farmlands have been intensively and contemporaneously developed. Krauser et al. (2022) examined the Dragon fruit plantation dynamics and recent urban expansion utilizing nighttime lights (NTL) from the Suomi National Polar-orbiting Partnership Visible/Infrared Imager/Radiometer Suite (VIIRS). They found a seasonal NTL signal important for differentiating various land uses on the ground. The authors employed the Breaks for Additive and Seasonal Trend (BFAST) algorithm to reduce and summarize seasonal trends in NTL data and a decision tree classifier to differentiate dragon fruit land use from city lights across the province. The results indicated that dragon fruit cultivation strongly increased after 2014 and reached a plateau after 2017. In recent years, the area of dragon fruit cultivation has experienced a slight decrease due to market fluctuations. The results also suggest that the dragon fruit cultivation of Bình Thuận has expanded to cover most inter-hill plains, reaching a spatial saturation due to the topographical constraints, and thus has begun to creep into the low-elevation foothill area. As a result, the province is experiencing a dual rural-urban land use with strong and contemporary developments in dragon fruit agriculture and the urban tourism industry, including building structure expansion. The authors concluded that dragon fruit plantation in southern Vietnam follows the land system transition pathways of many other agricultural contexts; however, the agricultural/urban transformation has profoundly altered the socioeconomic fabric of the region. This type of research contributes to the Earth Science Division’s equity and environmental justice strategy, specifically to further enable transdisciplinary science and applications that integrate physical and social science using NASA datasets.

In addition to changes in agricultural practices, climate change is generating new challenges in the ecosystems and the livelihoods of indigenous pastoralists, which practice extensive livestock production in the rangelands. Pastoralism is practiced in 75% of the world’s countries by an estimated 500 million people. Climate change is superimposed on geopolitical, social, and institutional changes in many of these countries. The Asian Drylands Belt (ADB) is a geographically, environmentally, and geopolitically diverse region that is confronted with a unique set of environmental and socioeconomic changes, including water shortage-related environmental challenges and dramatic institutional changes since the collapse of the Union of Soviet Socialist Republics. Chen et al. (2022) conducted a synthesis of the contemporary challenges for the sustainability of the social-environmental system (SES) of the ADB using a conceptual framework rooted in the three pillars of sustainability science: social, economic, and ecological systems. The authors found that while the sustainability of the ADB is affected by climate, globalization, rapid urbanization, labor migration, and other widespread environmental and socioeconomic changes, land use and land cover change is a key direct driver for the sustainability of the ADB landscapes and the region as a whole. The authors further recommend that place-based, context-dependent transdisciplinary approaches that focus on the human-environment interactions within and between regional landscapes are needed to meet the varied challenges across the region, with explicit consideration of specific forcings and regulatory mechanisms.

Agriculture and sustainability of social-environmental systems also impact food security which is one of the critical challenges in South/Southeast Asian (S/SEA) countries. Although total food production and productivity in the region have increased in previous decades, in recent years, the growth rate of food production has slowed down, mostly due to land-use change, market forces, and policy interventions. A book entitled "Remote Sensing of Agriculture and Land Cover/Land Use Changes in South and Southeast Asian Countries" by Vadrevu et al. (2022) captures the latest research on the remote sensing of agriculture and land cover/land use changes (LCLUC) focusing on mapping and monitoring crops, crop yields, biophysical parameter retrievals, multi-source data fusion for agricultural applications, and chapters on decision-making and early warning systems for food security. Total Chapters: 34; Total Authors: 200; Total pages: 607; Total illustrations: 224 (217colored; 17-black and white). The book is a collective achievement of renowned scientists working throughout S/SEA, the USA, and Europe. The book results from the NASA LCLUC Program-funded South/Southeast Asia (S/SEA) Research Initiative (SARI; www.sari.umd.edu) that Dr. Vadrevu is leading. SARI promotes innovative regional research, education, and training activities to enrich LCLUC science in S/SEA. The book is a valuable guide for researchers involved in satellite remote sensing of agriculture, land use/cover changes, spatial geography, ecology, geospatial technologies, and environmental science.

Biodiversity

Advances in Detection of Biodiversity Patterns

The combination of new remote sensing and in-situ technologies has led to major advances in the ability to detect and understand biodiversity patterns around the globe. As part of the SBG study, Rocchini et al. (2022) provide a review of the spectral species concept, relating field to remotely sensed data to measure biodiversity from space. They anticipate a refinement of this approach with new data from SBG, leading to the production of remotely-sensed essential biodiversity variables. In addition, in-situ tools to monitor species occurrence records have opened the door for greater understanding of species distribution shifts in response to environmental change. Townsend et al (2021) used in-situ camera trap biodiversity observations paired with remotely sensed environmental data to implement a network that links environmental satellite-derived data, e.g., Landsat-derived land cover, to biodiversity observations collected from trail cameras. Using the synthesis of both satellite and in-situ detection methods, this network provides environmental context to improve ecological monitoring and management by facilitating inference, prediction, and forecasting. In addition, these camera trap observations have led to new understanding of environmental impacts on biodiversity loss. For instance, Youngflesh et al (2021) utilized a large-scale remote time-lapse camera network and modeling framework to have an accurate but hands-off approach to obtaining data on Gentoo penguin nest failure rates across the entire Atlantic sector of the Southern Ocean. The study found that Gentoo penguin nest success was negatively affected by extreme weather, emphasizing how models such as this can help detect environmental stressors to aid in species conservation. Truelove et al (2022) showed that surveying biodiversity with newly available autonomous underwater vehicles (AUVs) equipped with eDNA sensors does not differ significantly in speed or accuracy from traditional field sampling. This finding opens the door for exponential growth in systematic biodiversity monitoring using a faster technology. This work will expand information for ecosystem management agencies on marine biodiversity patterns in data-poor regions of the world's oceans and provide complementary in-situ data on organisms for use with NASA satellite imagery.

In terms of remote sensing advances, Zhang et al (2022) demonstrated the ability of extremely high-resolution satellite data to advance marine biodiversity monitoring. Specifically, they obtained daily 3m resolution coastal and nearshore images from commercial Dove/Planetscope sensors through the NASA Commercial Smallsat Data Acquisition Program and extracted Sargassum features using a U-net deep learning computer model to track inundation events by Sargassum and other macroalgae on Miami and Cancun beaches. Dove/Planetscope data is a significant improvement from previous algae monitoring methods, as data is available within one day of overpass, can be collected more frequently, and is of a far higher resolution. This model can be used to track macroalgae worldwide and protect coastal ecosystems from the adverse effects of algae accumulation and possible harmful algal blooms.

The combination of remote sensing satellite and animal telemetry data has increased understanding of Earth system impacts on animal movement patterns. Kays et al (2022) developed the Movebank system, a database that allows tracking movements of free-ranging animals with remote sensing data and user-uploaded animal observations. Of note, this system leverages new systems (e.g., the International Cooperation for Animal Research Using Space ICARUS on the International Space Station) that track animal movement using satellite-based tracking of transmitting tags attached to organisms on the ground. All of this is joined with advances in modeling capability, as seen in Carlson et al (2021), who synthesized remote sensing environmental data with in-situ observations to track 45 white storks' foraging and breeding habitats. The individual resource selection models use individual preferences to enhance understanding of individual environmental responses in global change research.

Human impacts on global biodiversity

The capability of being able to regularly assess biodiversity changes across the world, even in the more remote areas, has never been more necessary as the impact of humans on global biodiversity continues to mount. Recent analysis by Simkin et al (2022) shows that rapidly urbanizing regions of sub-Saharan Africa, South America, Mesoamerica, and Southeast Asia, forecasted using the Coupled Model Intercomparison Project and the Land-Use Harmonization 2 project, will result in major biodiversity loss. Under current trends, up to 855 species are projected to be directly threatened by 2050 due to unmitigated urbanization. Coastal ecosystems are witnessing similar impacts driven by changing climate. Using Landsat imagery, McCarthy et al (2022) found that as of 2016, sea level rise in the Florida Big Bend region has led to an annual forest loss of 10 km^2. This is an 800% increase from 2003 rates. Also using Landsat imagery, Golet et al (2022) have shown that heavy management of the hydrological system in the Central Valley of California during early fall and late spring significantly reduces available habitat for migratory shorebirds. Nevertheless, increased understanding from work like this provides a means of mitigating negative human impacts. To help preserve these shorebirds, Golet et al (2022) outline strategies to offset the remaining food energy deficits, including improving habitat programs to better match the diet and migration patterns of the birds.

In a less direct manner, climate change due to human influence can intensify extreme weather events and cause negative impacts to global biodiversity. For example, Urquiza Muñoz et al (2021) used the LEDAPS (Landsat Ecosystem Disturbance Adaptive Processing System) to detect the occurrence of windthrows in the Northwest Amazon from 1988-2011. The recovery rate of trees in this region after extreme wind damaging the forests was 50% faster than in the Central Amazon, indicating higher productivity and adaptability to extreme events like windstorms. The varying rates of recovery in different Amazonian regions highlight the importance of extreme weather events like this on shaping forest structure and how the severity and frequency of natural disturbances being altered by climate change can impact tree populations differently.

Remote sensing observations have significantly advanced our understanding of global biogeographic patterns and their relationship with the Earth system. Given the difficulty of obtaining in-situ observations in marine systems, satellites provide a means of closing these knowledge gaps. For instance, Cael et al (2021) documented rapid marine community restructuring in the Atlantic and Pacific in response to gradual environmental changes. The authors related satellite-derived measures of nutrients, chlorophyll-a, biomass, and productivity to species richness and community structure. This work documents the interaction between living and physical Earth system processes and highlights the danger marine communities face under changing climate. Santora et al (2021) presented a framework for ecosystem monitoring in the California Current Large Marine Ecosystem– including krill distribution models from remote sensing data, seabird diets, etc. This approach is particularly important in areas that are data-poor or are difficult to access, for example, during and after the COVID-19 pandemic, and have the potential to contribute greatly to strategic ecosystem-based fishery management.

Remote sensing has also increased our awareness of terrestrial ecosystems and biodiversity. Pillay et al (2022) examined remote sensing derived range maps of vertebrates around the globe and found that tropical forests, covering 18% of Earth’s total land area, house 62% of Earth’s terrestrial vertebrates. The study applied low and high spatial resolution satellite datasets to quantify humid tropical forest clearing from 2000 to 2005. The rapid global loss of this habitat to logging poses a serious risk of local and global biodiversity loss. Outside of the tropics, Gudex-Cross et al (2022) showed that the length of annual snow and ice cover was the best predictor of local biodiversity. The authors compared similar areas with variations in remotely sensed winter characters and examined differences in the biological communities present. They found species richness declined in regions with more than three months of non-snow-covered frozen ground during the winter. In a rapidly warming world, species behavior and environmental interactions will undoubtedly change. Models such as these will be essential in forecasting the impact of climate change on species, communities, and ecosystems.

Impact of a changing climate on global biogeographic patterns
Laidre et al (2022) presented the first evidence for a genetically distinct and functionally isolated group of polar bears in Southeast Greenland that hunt and find refuge from climate impacts to their environment on a freshwater mélange of glacial ice. NASA National Snow and Ice Data Center data were used to track climate change impacts on polar bear distribution and abundance in the Arctic, showing that global warming affects specific polar bear subpopulations. Other works show how climate change is impacting behavioral patterns of wildlife. For example, Gilbert et al (2022) found that, over two winters that experienced warm and cold extremes, white-tailed deer adapted their behavior to conserve energy and increase survival. During anomalously cold temperatures, deer restricted activity to daylight hours and frequented habitats with the greatest likelihood of wind cover. These behavioral shifts reduce exposure to temperature extremes and render species more resilient to increasingly variable winter climates. Drought has been an additional driver of biological change. Huesca et al (2021) modeled blue oak mortality with AVIRIS hyperspectral data gathered during the intense 2011-2016 California drought. The team found Sierra Nevada populations of blue oak experienced mortality rates of 10% on average, reaching as high as 51%, with south-facing slopes at the greatest risk.

Space archaeology
Airborne laser scanning has proven useful for rapid and extensive documentation of historic cultural landscapes after years of applications mapping natural landscapes and the built environment. Recent integration of unoccupied aerial vehicles (UAVs) with LiDAR systems offers complementary data for mapping targeted areas with high precision and systematic study of coupled natural and human systems. Schroder et al. (2021) recently published results of data capture, analysis, and processing of UAV LiDAR data collected in the Maya Lowlands of Chiapas, Mexico in 2019. The authors studied six areas of archaeological settlement and long-term land-use reflecting a diversity of environments, land cover, and archaeological features which included pre-Hispanic settlements and agrarian landscapes. Agrarian features, domestic architecture, reservoirs, and public architecture were found to be dispersed in a mosaic across the landscape, and UAV LiDAR provided detailed samples that could be used to study how this mosaic influenced past land use and how past land use influences current land use and natural systems, such as hydrology. These data offer new collaborative opportunities to expand the use and application of these data with soil scientists, ecologists, and land use scientists.

Airborne and surface-based activities
Airborne and surface based (field) activities are restarting after the hiatus caused by the COVID-19 pandemic. Some lingering travel restrictions and access to some locations

have posed challenges to fieldwork, but most of the activities for the different programs have started again. Some of the highlights of field work for 2021-2022 are below.

ABoVE

ABoVE's field work and airborne measurements were very active in 2022 following a period of reduced activity due to the pandemic in 2020 and 2021. AVIRIS-ng collected imaging spectroscopy data over many research sites in both Alaska and northwestern Canada during July and August 2022. The airborne collections were significantly hindered by both smoke from wildfires and by bad weather in July, but August was much better. Field crews conducted concurrent field sampling. In addition, airborne sampling in the ABoVE domain was augmented with L-Band (UAVSAR), which conducted a successful airborne campaign over the ABoVE region in both Alaska and Canada in August 2022. The principal objective of these flights is to determine soil active layer depth and permafrost dynamics. Field crews across the region will support these flights with pertinent soil measurements. The plans to fly closely coordinated flights with the NASA P-Band radar were cancelled due to problems with the JSC G-3 aircraft.

GEDI

GEDI cal-val flights using LVIS were planned for southeast Asia in late 2022 but a decision was made to postpone these flights until April/May 2023 to allow more time for planning.

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.

Declining Arctic and Antarctic sea ice cover has been monitored and documented by NASA-funded research scientists since the beginning of the satellite record, and this work continued throughout the past year. *Parkinson and DiGirolamo (2021)* continue the record of multi-channel satellite passive microwave measurements of sea ice cover at both poles. This record, stretching back to the late 1970s, has long shown declining sea ice coverage in the Arctic throughout the entire time series, but up through 2015 revealed an overall increase rather than decrease in Antarctic sea ice cover. With these new observations of sea ice decline in the Southern Ocean since 2015, the 40-plus year satellite dataset now shows sea ice concentration decline in both hemispheres. The decreases in Arctic sea ice are expected based on observed increases in anthropogenic global warming, while the vagaries in sea ice concentration trends in the Antarctic are cause for more investigation.

As was the case last year, several significant papers were published in the last year using ICESat-2 to study sea ice properties, its thickness, and changes. *Petty et al. (2022)* provided a detailed description of improvements to the ICESat-2 sea ice products described in Petty et al. (2020), and produced estimates of winter Arctic sea ice thickness using sea ice freeboard measurements from ICESat-2 as well as snow loading estimates form the NASA Eulerian Snow On Sea Ice Model (NESOSIM) to compare with sea ice thickness measurements taken by CryoSat-2. The team used this analysis to highlight key changes in freeboard and thickness over the course of the existing ICESat-2 time series. These strong differences in total Arctic sea ice thickness observed across the three winters of the time series are linked to clear differences in multiyear sea ice thickness at the onset of each winter period. Their results show additional evidence of the importance of accurate snow depth representation when measuring interannual variability in winter Arctic sea ice thickness from satellite altimetry.

The simultaneous operations of NASA's ICESat-2 laser altimeter and ESA's CryoSat-2 radar altimeter continue to enable unique comparison studies of dual measurement techniques for sea ice altimetry. *Kacimi and Kwok (2022)* used ICESat-2 and CryoSat-2 sea ice freeboard measurements to examine the variability of monthly Arctic sea ice snow depth, thickness and volume between October 2018 and April 2021. Over the roughly 3-year measurement period, a decline in mean springtime Arctic sea ice thickness on the order of 30 centimeters is likely the result of roughly 50 centimeters of average thinning of multiyear sea ice. Snow depth estimates from each of these sensors reveal an overall thinner sea ice pack in the Arctic in the fall as well. These new observations add to a decades-long satellite record that shows a loss of one-third of the winter sea ice volume in the Arctic, largely driven by the decline of multiyear (versus first-year) sea ice coverage. *Fons et al. (2021)* used sea ice freeboard data from ICESat-2 to evaluate Antarctic snow freeboard retrievals from CryoSat-2; from these comparisons, they provide an updated snow freeboard retrieval method for CryoSat-2 datasets. Measuring sea ice freeboard from space is a critical initial step in estimating sea ice thickness. The improved snow freeboard retrievals display strong agreement with ICESat-2 freeboards both in the along-track data profiles and basin-scale monthly grids. While these corresponding datasets show adequate agreement between the two sensors, their assessment showcases the difficulties in comparing measurements from laser and radar altimeters due to wavelength and instrument footprint size differences.

New utilities for using ICESat-2 data to couple sea ice characteristics and ocean biology were also explored this year. *Bisson et al. (2021)* used data from Argo ocean float profiles that measure plankton characteristics and sea ice height and freeboard measurements from ICESat-2 to determine how Southern Ocean sea ice properties and under-ice phytoplankton characteristics are related. The team found that average sea ice freeboard is unrelated to under-ice phytoplankton counts, but when freeboard is more spatially variable, phytoplankton concentrations tend to be higher and prevalent at shallower depths. These results are not particularly intuitive, and suggest that the plankton communities' response to light conditions is complex and that plankton may respond in thriving, higher concentrations to an environment with varying light conditions. Also using ICESat-2 data to investigate light propagation in ice and snow, *Hu et al. (2022)* provided a suite of new methods to retrieve snow depth from ICESat-2 laser altimetry measurements alone (rather than relying on radar altimetry to provide measurements of this metric). To determine how to use ICESat-2's laser to measure snow depth, the team relied on a principle adapted from biologists and physicists who determined the average length of the path an ant travels inside its colony before emerging; the average time an ant walks around inside the colony before coming back is roughly four times the volume of the colony divided by its surface area. Similarly, a photon of light from a lidar enters the snow and bounces around as it is scattered by the snow particles until it exits and is collected by the telescope on ICESat-2. Using a model simulation and an equation almost identical to the one from the ant problem, the team discovered they could measure the average distance a photon traveled inside the snow before it's eventually measured by the lidar and determined the snow depth is half of that average distance. Being able to measure snow depth directly from laser altimetry and not relying on ancillary observations from radar altimeters would be a novel improvement for measuring snow depth from spaceborne altimeters.

Land Ice in the Climate System

The Greenland Ice Sheet is the largest single contributor to rising global sea levels, and monitoring the ice sheet and its many outlet glaciers is at the forefront of several important NASA-funded research projects. *Taubenberger et al. (2022)* performed the first assessment of seasonal dynamic thickness patterns of 37 of Greenland's outlet glaciers using ICESat-2 observations. The team classified glaciers by common patterns of seasonal thickness change over the ICESat-2 observational period (spring 2019 through fall 2020), and found similar patterns of seasonal thickness changes; however, over larger areas of the ice sheet, the data reveal little regional coherency in patterns of seasonal dynamic thickness changes (outside of southeast Greenland). This likely shows that large-scale atmospheric patterns and the movement of mesoscale weather systems aren't responsible for driving differences in patterns of seasonal thickness among glaciers. Instead, ocean forcing and unique glacier geometries/bed conditions (forces that impact terminus position) appear to be the largest drivers in these heterogeneous seasonal dynamic thickness patterns around the ice sheet. As ICESat-2 continues to collect data every 91 days over glaciers at both poles, these results will continue to be built upon to generate a robust time series of seasonal glacier velocity patterns and terminus position changes.

Boghosian et al. (2021) used high-resolution commercial satellite imagery in conjunction with imagery from Landsat-8 to observe and monitor meltwater estuaries on top of two ice shelves in northern Greenland (Petermann and Ryder ice shelves). Monitoring estuaries on top of these large outlet glaciers is critical for understanding ice shelf fracturing mechanisms and how these estuaries can inhibit large calving events. As the prevalence of meltwater increases on these ice shelves in a warming world, the formation and impact of these estuaries on ice shelf surface features will likely further promote longitudinal fracturing perpendicular to ice-shelf fronts and increase rectilinear iceberg formation. The team surmised that while this process is already underway on Greenland's ice shelves, ice shelf estuaries are likely to develop on Antarctica's ice shelves within the coming decades as the result of warming, which would lead to increased calving and acceleration of both ice loss and global sea level rise.

Vijay et al. (2021) performed a Greenland ice sheet-wide glacier classification based on seasonal velocity patterns derived from three years of Sentinel-1 radar data. Their classification system was primarily focused on two distinctive seasonal ice velocity patterns, with the first showing time periods of acceleration and deceleration during the melt season, and the second type displaying a longer period of deceleration from higher ice velocities in the winter and spring. They found that while glaciers meeting each of these different classification types vary from year to year, glaciers that experience periods of acceleration and deceleration during the melt season are more common in northern Greenland while glaciers displaying a longer period of deceleration from higher ice velocities in the winter and spring are more common in southern Greenland. These results show the highly variable impact on meltwater on glacier flow and subglacial drainage systems of Greenland's outlet glaciers.

The ice shelves that drain the Antarctic Ice Sheet to the surrounding oceans are critical to controlling the flow of glacier ice and thus are a key physical component of modulating sea level rise from Antarctic ice contributions. However, the availability of continent-wide data showing the growth and retreat cycles of ice shelves has not been widespread until recently. *Greene et al. (2022)* generated Antarctic-wide spatially continuous coastlines showing annual ice shelf front positions from 1997 to 2021 using several optical-band, thermal-band and radar satellite sensors, combined with observations of ice flow (velocity derived from the ITS_LIVE version 1 velocity mosaic and the InSAR-Based Antarctica Ice Velocity Map version 2; thickness derived from BedMachine Antarctica version 2). They show that over the time series studied, the Antarctic Ice Sheet experienced an overall loss of roughly 37,000 square kilometers of ice shelf area that will not be fully replaced before the next onset of major iceberg calving events, which they project to occur within the next 10 to 20 years. Additionally, they modeled the impacts of Antarctica's recent coastline changes in the absence of processes such as grounding-line movement or changes in grounded-ice geometry. The team also determined that iceberg calving and ice shelf thinning have also reduced the buttressing impact of ice shelves since 2007, which implies that further ice shelf retreat could potentially produce heightened sea level rise in the future.

Oceans in the Climate System

Oceans play a fundamental role in the Earth's system, modulating our planet's climate and weather by storing and transporting large quantities of heat, water, moisture, and carbon dioxide over the globe. The continuous exchange of properties between the ocean and the atmosphere influence climate and weather patterns over the globe by releasing the heat that fuels the overlying atmospheric circulation, releasing aerosols that impact cloud cover, absorbing and storing atmospheric carbon dioxide for millennia, and by releasing moisture that determines the fate of the global hydrological cycle.

NASA's Physical Oceanography Program supports a wide range of studies that quantify the ocean's role in the climate system by utilizing remote and in situ observations, numerical models and data assimilating systems. The program supports research that characterizes both ocean's intrinsic variability, its dynamics and thermodynamics, as well as ocean's interactions within the complex ocean-atmosphere-land-solid Earth system. Below are the most notable discoveries in 2021-2022 that advanced our understanding of the ocean's role in the climate system.

Ocean dynamics as a regulator of Earth's heat and freshwater budget

The oceans have an important role in the Earth's Energy Imbalance, a term referring to the difference between how much solar radiant energy is absorbed by Earth and how much thermal infrared radiation is emitted to space. Most of the excess of this energy goes into the oceans as heat, effectively delaying the full consequences of global warming. In order to measure Earth's Energy Imbalance, *Hakuba et al. (2021)* looked at both in situ ocean temperature profiles and satellite measurements of the ocean's thermal expansion, as well as relating it with the satellite observations of the ocean mass changes and sea level. New estimates by *Hakuba et al. (2021)* demonstrate the value of satellite-derived ocean observing systems such as gravimetry and altimetry to monitor Earth's Energy Imbalances and their superiority to the traditional ocean float estimates where in situ placement may not be possible.

A number of studies revealed a new interplay between the ocean heat uptake, ocean salinity, and the water cycle impacting the Earth's heat balance. For example, ocean regions with high surface salinity in evaporative regimes like subtropical gyres influence stratification that consequently leads to a higher rate of ocean heat uptake and sequestration of heat deeper into the ocean column (*Liu et al. 2022a*). A similar salinity contribution to the surface warming is found in the Southern Ocean, where *Liu et al. (2022b)* report that salinity-induced ocean stratification promotes deeper ocean heat uptake, thus reducing Earth's warming at the ocean surface and air-sea boundary. Complementary to Liu's findings, *Whitt (2022)* looked at low-salinity regions and examined the role of ocean freshening in rainy regions. Known for heavy rain events, tropical Pacific waters are prompted to the formation of fresh lenses that sit at the ocean surface, increasing ocean stratification, and inhibiting absorption of heat into the water column. Both studies, in salinity-high and salinity-low regimes, illustrate the role of ocean salinity as an important constraint in Earth's heat and freshwater budgets.

Ocean winds and currents regulate local weather and global climate

A new observational challenge to the ocean community to observe ocean winds and current simultaneously was recently posed by the Decadal Survey 2017, as one of the Targeted Observables to be addressed through the competitive Earth System Explorer program (see their Table 3.7). Studies below highlight a few science applications that will potentially benefit from this new observing capability.

Formation, development, and prediction of the ENSO events continues to be the focus of several studies within the program, owing to their influence on global weather and climate. *Whitt et al. (2022)* report that El Niños and La Niñas are triggered by a combination of surface winds and subsurface ocean currents. Through a series of data-constrained model experiments, *Whitt et al. (2022)* reconstructed ocean turbulent mixing in the tropical Pacific, consistent with that observed in the area. Based on their reconstruction and budget analysis, *Whitt et al. (2022)* concluded that most (90%) of the daily variance in ocean mixing is attributed to surface winds and surface ocean currents, which is responsible for triggering ENSO events.

Another example of the air-sea coupling was examined through a lens of teleconnections, connecting the changes in the Atlantic waters to those originating in the Indian Ocean. *Zhang et al. (2022)* attributes the formation of the Atlantic Niño to the oscillatory events in the Indian Ocean, known as the Indian Ocean Dipole. During the warm phase of the Indian Ocean Dipole, when the western Indian Ocean is warmer and rainier than the eastern part, the easterly trade winds are weakened. The same weakening of the trade winds leads to the warming of the central and eastern equatorial Atlantic. Those warm anomalies ultimately trigger the Atlantic Niño, which influences local and global weather patterns.

Above the tropical latitudes, *Ramadan et al. 2022* examine the effect of ocean winds and currents in the polar oceans, focusing on the dynamics of the Seasonal Ice Zone around Antarctica. While previous studies attributed the changes in sea ice within the Seasonal Ice Zone to wind-only effects, *Ramadan et al. 2022* showed a more complex interplay between the ocean winds and currents, resulting in a more sporadic circulation and ice dynamics within the Zone. They showed, for example, how the ocean winds encourage upwelling along the sea ice edge, while ocean currents encourage downwelling along the outer edge of the Seasonal Ice Zone, illustrating the importance of future observing systems that can capture both ocean winds and currents simultaneously.

Ocean's role in marine extremes and coastal hazards

An emerging focus of the NASA Ocean Physics program are studies of the ocean extremes. Observational evidence suggests that, in addition to low-frequency climate trends, there are measurable changes to the ocean extreme events, such as marine heatwaves, storms, high-wind events, flooding, etc. A number of studies this year investigated the physics of the ocean's extreme events, interpreting the underlying mechanisms of the extremely active 2020 hurricane season in the Gulf of Mexico. *Dzwonkowski et al. (2021)* attributes intensification of Hurricanes Marco and Sally in 2020 to a combination of strong winds and downwelling ocean currents, which pump the heat from the surface towards the bottom of the shelf. The continued reheating of the upper ocean and offshore transport of the warm coastal waters further enhanced shelf thermal energy, intensifying the subsequent storm. The compound mechanism explains the rapid intensification of both Hurricanes Marco and Sally before their landfalls, which caused more than $7 billion USD in damage to the coastal communities.

Another area of research to improve our understanding of ocean extremes is wave-current interaction during high-wind events, such as tropical cyclones. Ocean currents can modify wave heights and lead to extreme wave conditions, but they are commonly overlooked in wave forecasts. *Sun et al. (2022)* used satellite radar altimetry data and wave modeling to quantify the effects of ocean currents on the surface waves generated during a tropical cyclone event in the Arabian Sea. The case study documents how waves can propagate from tropical cyclone eyewalls due to the current-induced refraction and conclude that in the interplay between the underlying background current and the cyclone-induced current, it is the former that dominates the wave structure dynamics. Their findings highlight the importance of accounting for the ocean currents in order to accurately predict the impact of tropical cyclone generated waves on coastal regions.

Integrated Earth System and Modeling

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

- The NASA GISS Model E, an Earth system model which is utilized for multidecadal studies of the climate system and understanding the various anthropogenic and natural factors influencing global change on decadal to multidecadal time scales.
- The GEOS Modeling System, which includes the GEOS modular Earth system model, the GEOS data assimilation system, the GEOS coupled chemistry/climate model, and the GEOS chemistry and transport model.
- The NASA Unified WRF model, which is directed toward developing a comprehensive representation of the Earth system at regional scales.
- The Estimating the Climate and Circulation of the Ocean (ECCO) assimilation system, jointly supported by the Physical Oceanography and MAP components of the CVC focus area. Its goal is to generate an accurate, high resolution, coupled

ocean/sea ice/biogeochemistry atmospherically-consistent state estimate for research applications and prediction.

Results from studies utilizing these and other MAP supported modeling efforts focused on characterization of the behavior of the Earth system included:

Climate modeling advances

A long-standing thread of Climate/Earth system modeling advances is the development of higher resolution models capable of improved resolution of Earth system processes. The next-generation global climate model from the NASA Goddard Institute for Space Studies, GISS-E3, contains many improvements to resolution and physics that allow for improved representation of tropical cyclones (TCs) in the model. Russotto et al. [2022] examined the properties of TCs in two different versions of E3 at different points in its development cycle, run for 20 years at 0.5 degree resolution, and compares these TCs with observations, the previous generation GISS model, E2, and other climate models. E3 shares many TC biases common to global climate models, such as having too few tropical cyclones, but is much improved from E2. E3 produces strong enough TCs that observation-based wind speed thresholds can now be used to detect and track them, and some storms now reach hurricane intensity; neither of these was true of E2. Model development between the first and second versions of E3 further increased the number and intensity of TCs and reduced TC count biases globally and in most regions. One-year sensitivity tests to changes in various microphysical and dynamical tuning parameters were also examined. Increasing the entrainment rate for the more strongly entraining plumes in the convection scheme increases the number of TCs, and variations in divergence damping did not have a strong effect on simulated TC properties, contrary to expectations based on previous studies. Overall, the improvements in E3 make it more credible for studies of TC activity and its relationship to climate.

Much of northern Eurasia experienced record high temperatures during the first three months of 2020, and the eastern United States experienced a significant heat wave during March. Schubert et al. [2022] showed that these episodes of extraordinary warmth reflect to a large extent the unusual persistence and large amplitude of three well-known modes of atmospheric variability: the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), and the Pacific–North American (PNA) pattern. A “replay” approach was used in which simulations with the NASA GEOS AGCM were constrained to remain close to Modern Era Reanalysis for Research and Applications -2 (MERRA-2) reanalysis fields over specified regions of the globe in order to identify the underlying forcings and regions that acted to maintain these modes well beyond their typical submonthly time scales. The study shows that an extreme positive AO played a major role in the surface warming over Eurasia, with forcing from the tropical Pacific and Indian Ocean regions acting to maintain its positive phase. Forcing from the tropical Indian Ocean and Atlantic regions produced positive NAO-like responses, contributing to the warming over eastern North America and Europe. The strong heat wave that developed over eastern North America during March was primarily associated with an extreme negative PNA that developed as an instability of the North Pacific jet, with tropical forcing providing support for a prolonged negative phase. A diagnosis of the zonally symmetric circulation showed that the above extratropical surface warming occurred underneath a deep layer of tropospheric warming, driven by stationary eddy-induced changes in the mean meridional circulation.

Chemistry/climate modeling advances

Global modeling of chemistry/climate interactions is a great computational challenge because of the high computational cost of integrating the kinetic equations for chemical mechanisms with typically over 100 coupled species, limiting the utility of coupled chemistry/climate models. Shen et al. [2022] present an adaptive algorithm to ease this computational bottleneck with no significant loss in accuracy and apply it to the GEOS-Chem global 3-D model for tropospheric and stratospheric chemistry (228 species, 724 reactions). The approach was inspired by unsupervised machine learning clustering techniques and traditional asymptotic analysis ideas. Species are locally defined in the mechanism as fast or slow on the basis of their total production and loss rates, and the coupled kinetic system is solved only for the fast species assembled in a submechanism of the full mechanism. To avoid computational overhead, the species are first partitioned from the full mechanism into 13 blocks, using a machine learning approach that analyzes the chemical linkages between species and their correlated presence as fast or slow in the global model domain. Building on these blocks then 20 submechanisms are preselected, and then the model picks locally and on the fly which submechanism to use based on local chemical conditions. Because many species in the full mechanism are important only in source regions, the effective size of the mechanism is reduced by 70 % globally without sacrificing complexity where/when it is needed. The computational cost of the chemical integration decreases by 50%.

Nitrous oxide (N2O) is the third most important anthropogenic greenhouse gas and a major ozone-depleting substance. Its main sources include anthropogenic activities (mostly agriculture) and natural emissions from ocean and soils. However, emission estimates for individual sources are highly variable due to uncertainties in N2O lifetime estimates and partitioning among sources. Liang et al. [2022] derived annual global N2O emissions for 1990–2019 using NOAA Global Monitoring Laboratory (GML) surface N2O observations and the N2O lifetime calculated in the NASA GEOS-5 chemistry climate model. The inferred global mean N2O emissions has gradually increased from ∼15.8 TgN/yr in the early 1990s to ∼17.8 TgN/yr in the 2010s. This implies that anthropogenic N2O emissions have grown rapidly from ∼6.7 TgN/yr in the 1990s to about ∼8.7 TgN/yr in the 2010s, a ∼30% increase. With specially designed N2O isotopic tracers in 3-D GEOSCCM, the study estimates that, on global average, stratospheric enrichment contributes about +7.7‰/yr, +7.6‰/yr, +8.0‰/yr to tropospheric δ15Nα, δ15Nβ, and δ18O budget, respectively. To balance the global mean isotopic signature for pre-industrial terrestrial sources of δ15Nα ∼ 6.7‰, δ15Nβ ∼ −12.6‰, δ18O ∼ 35.4‰, a 3-dimensional isotopic budget simulation using the GEOSCCM suggests global mean anthropogenic isotopic signatures in the recent decades are δ15Nα ∼ −18‰, δ15Nβ ∼ −20‰, δ18O ∼ 19‰. These anthropogenic isotopic estimates are significantly lighter than results from one-box atmospheric model-based estimates with the largest difference seen for δ15Nβ. More surface isotopic measurements are needed to better quantify the N2O isotopic signatures.

Land and land/atmosphere coupling modeling advances

Rahman et al. [2022] tested the hypothesis that jointly assimilating satellite observations of leaf area index and surface soil moisture into a land surface model improves the estimation of land vegetation and water variables. An Ensemble Kalman Filter was used across the Contiguous United States from April 2015 to December 2018. The results showed that the assimilation of the leaf area index mostly improves the estimation of evapotranspiration and net ecosystem exchange, whereas the assimilation of surface soil moisture alone improves surface soil moisture content, especially in the western US, in terms of both root mean squared error and anomaly correlation coefficient. The joint assimilation of vegetation and soil moisture information reduces errors (and increases correlations with the reference datasets) in evapotranspiration, net ecosystem exchange, and surface soil moisture simulated by the land surface model. This work moves one step forward in the direction of improving the estimation and understanding of land surface interactions in climate models using a multivariate data assimilation approach.

Ocean/atmosphere coupled modeling advances

The spatial distribution of ocean-induced melting beneath buttressing ice shelves is often cited as an important factor controlling Antarctica's sea-level contribution. Using numerical simulations, Joughin et al. [2021] investigated the relative sensitivity of grounded-ice loss to the spatial distribution and overall volume of ice-shelf melt over two centuries. Contrary to earlier work, the paper reports only minor sensitivity to melt distribution (<6%), with a linear dependence of ice loss on the total melt. Thus, less complex models that need not reproduce the detailed melt distribution may simplify the projection of future sea level. The linear sensitivity suggests a contribution of up to 5.1 cm to sea level rise from Pine Island Glacier over the next two centuries given anticipated levels of ocean warming, provided its ice shelf does not collapse because of other causes.

<u>Section 1.1.8.4</u> 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.

Lithospheric Processes

Lithospheric structure and dynamics, and interactions between these processes and the oceans, hydrologic system, and atmosphere are critical to understanding the Earth system.

This includes the motion and rotation of tectonic plates, elastic properties of the crust and mantle, and the effects of surface loading resulting from surface water, ground water, other fluids, glaciers, and ice sheets. Hydrogeodesy continues to develop as a field of study, with important advancements in understanding connections between natural and anthropogenic fluid flux and solid-Earth deformation. Many lithospheric process-related studies have advanced to support upcoming missions, such as seafloor and mineral mapping, and others are related to how geodesy can be used to measure the effect of fault dynamics.

Hydrogeodesy

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

Loading or unloading due to watershed volume changes can be measured by GNSS, InSAR, and Gravimetry and can be used to derive the amount of terrestrial water storage (TWS) available. Han et al. (2021) used GRACE-FO gravity data processing to quantify changes in water storage impacted by heavy rainfalls and flooding in Eastern Australia in March 2021. They were able to identify a high speed of ground water recharge and wet antecedent soils that resulted in the flooding events. The study demonstrated that GRACE-FO data could be used for rapid 1-3 day processing of mass changes during extreme weather events.

Anthropogenic influences, such as ground water injection and extraction, can affect TWS in a region to such a large degree that it can be remotely measured using InSAR, GNSS, and GRACE. The changes in lithospheric stress that occur during injection and extraction can lead to cascading hazards. Deng et al. (2022) identified how fluid injection and oil and gas extraction caused induced seismicity in Texas. They used InSAR to monitor three study sites and found inflation related to injection at site one, slight subsidence and many earthquakes related to extraction at site two, and significant subsidence and earthquakes at the third site related to a combination of groundwater and oil/gas extraction. Although there were several factors influencing the third site, all earthquakes seemed to correspond to the occurrence of fluid injection. Lundgren et al., (2022) studied how the San Andrea fault is being impacted by groundwater withdraw in California's Central Valley using finite element modeling of InSAR data. They focused on the period of the 2006-2010 drought and found that lower crust and upper mantle viscosity changes that occurred as a result of variations in groundwater storage enhance uplift and stress changes at the San Andreas Fault. This stress can accumulate with time and is increased during periods of drought and groundwater consumption.

Seafloor Mapping

With the planned launch of NASA's Surface Water and Ocean Topography (SWOT) mission just over a year away, there has been an increased interest in mapping seafloor topography with existing techniques that can be applied and leveraged by SWOT. Sandwell et al. (2021) use gravity measurements obtained from six different satellite radar altimetry missions to provide a new understanding of the topography and tectonics of deep oceans to determine which altimeter can best measure the marine gravity field. Although sea surface roughness and ocean waves created difficulties when recovering small scale gravity features, all 5 altimeters provided some value when making assessments. The Satellite with ARgos and ALtiKA (SARAL/ALtKa) altimeter was identified as having the highest amount of precision and if the mission continues to run for another few years the authors believe it will become the most important altimeter for deep ocean gravity field recovery currently in orbit.

Mineral Mapping

Using image spectroscopy techniques, satellite sensors acquiring imagery in the VNIR, SWIR, and TIR wavelengths are able to determine surface compositions. Thompson et al. (2022) used laboratory spectra of rock samples heated between 473 to 1573K to calculate how spectra vary at high temperatures while accounting for all significant error sources. They used these data to calibrate a spectrometer to produce spectra at high temperature that matched their low temperature counterparts. These calculations can be used to better interpret satellite surface temperature, emissivity, and composition of cooling lava flows, which are important measurements in lava cooling and flow propagation models.

The Earth Mineral dust source InvesTigation (EMIT) sensor launched to the ISS on July 14, 2022, and will be used to map the surface mineralogy of Earth's dust source regions using spectroscopic analysis to determine the role they play in dust formation and radiative forcing. Meng et al. (2022) developed a parameterization for the emission of super coarse dust in atmospheric models. They found that possible errors in these models of dust deposition processes during transport decrease the effective dust aerosol density by an order of magnitude of its physical value of ~2,500 kg/m3. They concluded that the underestimation of super coarse atmospheric dust by models is in part due to the underestimation of the emission of super coarse dust and likely in part due to errors in deposition processes.

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. Saylor et al. (2021) used a multifractal analysis of a seismic moment distribution obtained by applying a genetic algorithm to InSAR inversion to map out sub-surface fault systems. A generic algorithm was used to account for nonlinear seismic moment changes and revealed multifractal properties that are commonly missed in other linear algorithms. This study was performed as a proof-of-concept to demonstrate how this new method and algorithm can invert the parameters of many seismic sources simultaneously and improve future fault mapping efforts. Goulet et al. (2021) studied surface ruptures from the 2019 Ridgecrest earthquake to evaluate the abilities of field measurements and UAS imaging, and airborne LiDAR to capture co-seismic deformation on or near fault ruptures. While all three techniques captured the key features that are important for displacement design of distributed infrastructure, the use of remote sensing methods in combination with field measurements presented an advantage over the use of any single technique, and the author recommended using multiple complementary techniques when making these measurements.

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. Chorsi et al. (2021) studied the Monte Cristo Range earthquake that occurred on May 15, 2020, which was well-recorded by both seismic and geodetic instrumentation including InSAR, GNSS, and ground mapping due to the arid location of the surface rupture. The authors were able to construct a series of slip models by integrating several independent data sets that were consistent with geodetic data, aftershocks measurements, the mapped surface rupture, and laboratory data. The data collected provide a new approach to seismic hazard assessment for earthquakes in rapidly evolving tectonic regions.

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. Brandenberg et al. (2022) focused on documenting Ridgecrest ground deformations including surface fault rupture using GPS, structure from motion, and Lidar during five separate ground campaigns shortly after the earthquake. The authors processed and collated these data so that other researchers may utilize them to better interpret the results from this seismic sequence. Donnellan et al. (2022) studied how the aftershocks of the Ridgecrest earthquake damaged several of the Trona Pinnacles using photogrammetric data. These pinnacles were used as an analog for constraining past earthquake shaking intensity and used to calculate the quasi static, horizontal acceleration required to break the spire at its base. They found that the shaking during the main shock likely generated tensile stresses in excess of the pinnacle's bulk strength, thereby making it vulnerable to collapse in subsequent aftershocks. Milliner and Donnellan (2022) used daily observation from Planet Labs satellite imagery to separate the types of surface deformation between the July 4 foreshock and July 3 mainshock of the Ridgecrest earthquake. They found that with these optical data they were able to uniquely separate the surface fracturing and deformation between these two events. These results can help guide and validate field survey observations to help understand which faults ruptured when and constrain slip inversion models for more accurate estimates of stress changes induced by the foreshock imposed on the surrounding faults.

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. Stephens and Wauthier (2022) used InSAR data to model the spatio-temporal evolution of the magma plumbing system at Masaya Caldera from 2011 to 2019 during an open-vent eruptive period. They observed degassing-induced pressurization of the central reservoir between 2012 and 2015 and magma being supplied to the reservoir in mid-2015 which led to the appearance of the summit lava lake in late 2015. This magma supply continued, stopped, and then eventually depressurized from 2017 to 2019. This study helped researchers better understand and map the sub-surface processes occurring during eruption. Wang et al. (2022) used point source InSAR and GNSS analysis and source inversion with finite element models to interpret the inflation of Okmok Volcano from 2008 to 2020. Following the 2008 eruption Okmok has inflated at a variable rate which the authors attribute to a spatially stable magmatic source located in the central caldera believed to be the same source that produced the 1997 and 2008 eruptions. They demonstrated how InSAR data combined with an Ensemble Kalman Filter can be used to assimilate the time-series deformation for the determination of source location and track the temporal evolution of the source strength.

Yue et al. (2022) examined the impact eruptions can have on the atmosphere when they studied how the La Soufriere volcanic eruption can launch atmospheric gravity waves into space. They observed mesoscale concentric gravity waves in the mesopause airglow layer following the La Soufriere volcano eruption in April 2021 as well as nightglow gravity waves which were observed by the VIIRS Day-Night Band. The launch of gravity waves was highly correlated with the elevated ash plume from explosive eruptions and could be used to provide direct evidence of lithosphere-atmosphere-ionosphere coupling via the generation and propagation of gravity waves.

Developing new methods to monitor for volcanic ash remains an important aspect of volcanology as these eruptive products can impact the local population and ecosystem, hemispheric and global climate, and safe aviation routes. Krotkov et al. (2021) developed a low-latency quantitative retrieval algorithm for Day-Night monitoring of volcanic SO2 and ash from OMPS and VIIRS. These data will be used by Volcanic Ash Advisory Centers to improve their monitoring of ash clouds and track the dispersion of long-lived SO2/aerosol clouds when ash is not directly detectable. These improvements would increase frequency and add an element of night monitoring. The authors argue both are lacking in the current GOES-based monitoring algorithm. Williams and Ramsey (2022) used ASTER TIR emissivity data to analyze the ash emissions of the 2020 Nishinoshima eruption. By performing linear deconvolution of the ASTER data using the ASTER volcanic ash library they were able to determine the composition, particle size, and distribution of the ash plume. This demonstrated how ASTER and other similar sensors can be used for volcanic ash monitoring. Carn et al. (2021) wrote an EOS article to anticipate how major volcanic eruptions can impact climate. They outlined how NASA's rapid response plan for gathering atmospheric data amid major eruptions, paired with effort to improve eruption simulations, will be an important advance for volcano science and a powerful means to assess the climate impacts of future large explosive eruptions.

Recently, monitoring sub-marine volcanic eruptions has gained the attention of the remote sensing community as multispectral data have proven useful in identifying the occurrence of these eruptions. Zheng et al. (2022) trained a machine learning algorithm to detect pumice rafts produced during sub-marine eruptions using Landsat 8 and Sentinel-2 data. They found a large number of previously unreported pumice rafts in images acquired from 2017 to 2021. Although many of these rafts were the result of the remobilization of pumice clasts from previous eruptions, the authors note that this method may have significant implications for submarine eruption detections and volcanic stratigraphy.

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. Handwerger et al. (2022) examined landslide sensitivity and response to precipitation changes in wet and dry climates at 39 landslides that occurred in California between 2015 and 2020 using open-access InSAR data. They found that despite the large differences in hydroclimate, these landslides exhibited surprisingly similar behaviors and hydrologic sensitivity, which was characterized by faster than average velocities during wetter than average years, as well as slower than average velocities in drier than average years, once the impact of the drought diminished. The authors note that their findings further confirm landslide sensitivity to climate change under diverse hydroclimate conditions and highlight the need to establish a long time series of landslide behaviors that can be used to better predict future landslide activity.

InSAR, GNSS, and optical techniques have recently been employed to effectively track the evolution of slow-moving landslides. These findings are critical because the mechanisms that occur during the landslide event can be directly observed in their slow-moving counterparts. Vinueza et al. (2022) developed a new method to systematically detect and quantify accelerations and decelerations in displacement rates of slow-moving landslides by applying an outlier detector to InSAR times series. The application of this new method resulted in increased information on the dynamics of the surface displacement of hillslopes and provides an objective way to identify changes in displacement rates. These measurements can be used to study the physical behavior of a slow-moving slope or for regional hazard assessment by linking the timing of changes in displacement rates to landslide causal and triggering factors.

Flooding and Tsunamis

Floods and Tsunamis are directly impacted by and can originate from solid-Earth related triggers. Han et al. (2022) used GRACE-FO data acquired during the 2020 monsoon season in Bangladesh to monitor how premature soil saturation can lead to flooding. In 2020, Bangeldesh had a monsoon period that was preceded by a premonsoon cyclone. In late July 2020, early in the monsoon season, the authors used GRACE-FO data to detect a peak water storage anomaly across Bangladesh. As a result, monsoonal flooding started earlier, lasted longer, and was more severe than in previous years. The authors use this paper to highlight the importance of including antecedent soil moisture condition in flood forecasting and warning practices.

Tsunamis typically originate from an earthquake or landslide event and can produce flooding on a large scale that can be difficult to map or forecast. Grzan et al. (2021) developed a new tsunami warning system that links Total Electron Content (TEC) disturbances in the ionosphere detected by GNSS satellites to maps of inundated areas along affected coastlines using a pipeline of earthquake, ionosphere, and tsunami simulations. They developed a simulator called Tsunami Squares that employs a unique method of propagating water according to shallow water theory to propagate waves from sea to land. This new simulator is impactful because it allows flooded areas along the coast to be mapped, cuts back on computational time and cost, and negates the need for third party runup calculating software.

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. Mark et al. (2022) examined the lithospheric erosion in the Patagonian slab window and linked it to implications for glacial isostasy. They present the first regional seismic velocity model covering the entire north-south extent of the slab window and found a very low seismic velocity within and around a gap in the subducting plate beneath Patagonia, as well as thinning of the rigid South American lithosphere overlying the gap.
The authors state this provides key evidence to support the previously hypothesized connection between post-Little Ice Age anthropogenic ice mass loss and rapid geodetically observed glacial isostatic uplift. Sauber et al. (2022) determined how changes in surface mass in southern Alaska influenced crustal deformation and seismicity amidst rapid tectonic deformation. They examined how since the end of the Little Ice Age, the glaciers of southern Alaska have undergone extensive wastage, this combined with seasonal mass fluctuations due to snow accumulation and rainfall produce stress changes in the solid Earth that modulate seismicity and promote failure on upper crustal faults. The authors found long-term ice wastage may promote major earthquakes in time, though it represents a second-order perturbation on top of the rapid tectonic loading from seasonal changes.

The GRACE and GRACE-FO satellites are highly utilized when collecting mass change measurements and several researchers in the past year have worked to try to improve these measurements. Deccia et al. (2022) used a multi-objective genetic algorithm to design satellite constellations of GRACE-type smallsat pairs with orbits that are optimally designed to recover gravity variations of sufficient resolution at a range of temporal frequencies. The authors found that the resulting constellations would have an inherently improved spatiotemporal performance, which reduces temporal aliasing errors and allows the characterization of daily mass-change effects. Ghobadi-Far et al. (2022) performed an along-orbit sensitivity analysis of the GRACE-FO laser-ranging interferometer (LRI) measurements for sub-monthly surface mass variations. They present an alternative methodology in terms of line-of-sight gravity difference (LGD) to fully exploit the higher precision LRI measurements for examination of sub-monthly mass changes. They demonstrate the LRI are capable of detecting mass variability associated with the high-frequency oceanic gyre in the Argentine Basin, oceanic mass changes in the Gulf of Carpentaria, and river water variation in the Amazon Basin. They identify the issue that these processes cannot be adequately studied using the standard monthly-mean data products from GRACE-FO mission and that an along-orbit analysis would improve the temporal coverage. The increase in temporal resolution is especially suitable for quantifying temporal and spatial evolution of extreme, rapidly changing mass variations and has implications for the hydrosphere, cryosphere, solid Earth, and oceans.

Tectonics

Tectonics influence large regions of the Earth and can provide insight into the deep Earth as well as help to explain the occurrence of orogenic and earthquake events. Brink et al. (2022) studied the mature diffuse tectonic block boundary that was revealed by the 2020 Puerto Rico seismic sequence in the southwest of the country. They found that the T-axis of the moderate earthquakes further matches the extension direction previously measured on post early Pliocene (~>3 Ma) faults. The observed deformation may represent the southernmost part of a diffuse boundary, the Western Puerto Rico Deformation Boundary, which accommodates differential movement between the Puerto Rico and Hispaniola arc blocks. The authors conclude that we should not expect a single large event in this area but similar diffuse sequences in the future. Klein et al. (2021) studied transient deformation in California from two decades of 1000 continuous GPS stations to distinguish tectonic and nontectonic transients from secular motion. The observed post-seismic strain rate variations as large as 1,000 nstrain/year with moment releases equivalent up to an Mw6.8 earthquake and found significant secular differences up to 10 mm/year with the fault slip model. The authors demonstrate the utility of the kinematic datum by improving the accuracy of high-spatial-resolution 12-day repeat cycle Sentinel-1 Interferometric Synthetic Aperture Radar displacement and velocity maps.

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.

NASA-ISRO Synthetic Aperture Radar (NISAR) Science Team

The NISAR project incorporated the "smart-tasking" tool capabilities for urgent response into the mission system, with implications for enabling ESI-relevant geohazards research. The tool can accept urgent response requests from registered users to facilitate the collection, disposition, and forwarding of requests to the NISAR mission operations team, thereby aiding in disaster relief and mitigation during operations by systematically handling more and varied urgent response scenarios. In the past year, NISAR mission operations team exercised the tool, and demonstrated its utility to streamline their operations. The tool automatically polls early warning services like the USGS PAGER (Prompt Assessment of Global Earthquakes for Response) system, discovers the location of events that meet the preset threshold of severity, and issues a request to mission operations in a predefined format.

The NISAR Project conducted a workshop June 6-7, 2022, at UC Davis on Subsidence and Resource Extraction Applications. The main objective of the workshop was to identify the highest priorities of the end-user community that would facilitate their ability to use NISAR data to improve operations. The workshop brought together participants from local, state and federal agencies, academia, NASA headquarters and the NISAR Science Team to discuss end users' needs within the context of the mission capabilities, provide input on high value end user information needs that can be addressed with radar remote sensing, and generate a roadmap for joint activities that will improve the utility and utilization of NISAR data when they become available. The outcomes are being documented in a workshop report.

The NISAR Project created video science stories to highlight NISAR contributions including volcanic processes. These are geared toward the general public, with interviews with scientists and community stakeholders. This year the team produced a video highlighting the multi-cultural, international nature of the project team responsible for building the flight system and conducting the science. The video emphasized the challenges and sense of community in building such a complex system by two agencies on opposite sides of Earth, and uniqueness of the long-wavelength dense time series comprehensively covering Earth's volcanoes for modeling and eruptive prediction.

Following on the success of the 2020 and 2021 UNAVCO virtual training classes for geodetic imaging, members of the NISAR project science and algorithm development team will repeat the training in August 2022. This year again, 150 students have been selected out of a pool of nearly 450 applications. Once again, the training will last 5 days, and use processing scripts and algorithms that will support NISAR geodetic processing on the cloud. The cloud-based processing system is the Alaska SAR Facility's OpenSARLab. ASF is the NISAR DAAC.

The NISAR science team continued to develop activities for diversity, equity, inclusion and access under the IDEA committee led by Susan Owen at JPL. In the past year, the team conducted four 1-hour classes entitled "Unlearning Racism and Bias in NISAR (URBN)", designed to promote understanding of such issues within the NISAR project, and what the team can do about it. The class is modeled after the Unlearning Racism in Geoscience Education (URGE) curriculum and a second class will be offered in September 2022. The IDEA committee is also working with NASA to identify relevant institutions for partnering, and opportunities for engaging communities in environmental justice programs where NISAR remote sensing data may have an impact.

The calibration/validation team, led by Bruce Chapman at JPL, continues to prepare for launch by conducting geodetic cal/val exercises that leverage ESI capabilities. In 2021-2022, the team, in collaboration with the University of Oklahoma and the Alaska Satellite Facility, installed six newly constructed 2.8 m on-a-side corner reflectors in Alaska and Oklahoma to test deployment procedures. The Oklahoma reflectors were successfully observed by UAVSAR, NASA's L-band airborne testbed, and by ASAR, the ISRO L- and S-band SAR instrument deployed on the UAVSAR platform for flights in the US in 2021 and performed as expected. The cal/val team has begun discussions between NASA, UNAVCO, and the National Science Foundation to coordinate deployments of GNSS receivers in Greenland and Antarctica starting in 2023. The cal/val team has also been establishing contracts and partnerships for collecting biomass measurements at globally representative forest biomass cal/val sites. These developments have been incorporated in a new version of the calibration and validation plan, to be released in August 2022.

The Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) Facility

During the time period from July 01, 2021 to June 18, 2022, UAVSAR conducted 36 science/engineering flights totaling 186 flight hours. All flight lines were acquired in the United States: 373 flight lines were imaged with the L-band radar and 42 with the P-band radar. The Project supported 7 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 2 Rapid Response events: California's Caldor Fire and Louisiana's Hurricane Ida. In the campaigns described below, PIs led interdisciplinary teams that included universities and US agencies, leveraging UAVSAR to provide valuable high spatial resolution and temporally targeted SAR data, as well as supporting preparations for NISAR.

In a study led by Dr. Zhong Lu (Southern Methodist Univ.), the UAVSAR P-band instrument was used to image deep-seated landslides in the US Pacific Northwest. One of the goals was to assess the potential for mapping deformation under densely-forested areas. The team was able to identify 55 active landslides in total of which 39 were not included in the USGS landslide inventory, and 40 were not detected by the L-band sensor ALOS/PALSAR. Flights were conducted in December 2021 and are planned to be repeated in 2022.

UAVSAR L-band observations were employed in a rapid response effort led by Dr. Cathleen Jones (NASA/JPL) to map the October 2021 Huntington Beach oil spill. Results were used to inform monitoring and clean-up efforts by NOAA. Dr. Francis Monaldo (Univ. Maryland) led a related effort in coordination with the USGS to image a permanent oil seep location off the Santa Barbara coast. Dr. Monaldo's team conducted two campaigns (October and June) and the resulting imagery is subsidizing oil spill algorithms in preparation for the NISAR instrument.

Geodetic Imaging Enabling Research

InSAR and GPS data availability and processing methods are critical to many avenues of ESI science, while also providing high-resolution maps and time series of surface deformation applicable to many scientific and applied studies. Atmospheric, vegetation, and anthropogenic derived noise are particularly prevalent and challenging components of space based InSAR observations that must be accounted for to accurately derive underlying surface displacements in the data. Aati et al. (2022) devised a new approach for 2-D and 3-D precise measurements of ground deformation from optimized registration and correlation of optical images and ICA-based filtering of image geometry artifacts. They attempt to extract high-quality surface displacement in 3D based on the correlation of multi-date and multi-platform high resolution optical imagery. When a large enough volume of data is available, they attempt to separate the deformation signal from the artifacts due to the satellite jitter and misalignment of the CCDs, which, together with topographic artifacts, are the main source of noise in the measurements. With their technique, the authors were able to generate high quality measurements of coseismic ground displacement with a ground sampling distance of 2.4 m, and uncertainties at the 90% confidence level on the NS, EW and vertical displacement measurements of 0.6 m, 0.7 m, and 0.6 m respectively. Hu et al., (2021) trained a machine learning algorithm to characterize tectonic, hydrological, and anthropogenic source of active ground deformation in California. They trained the algorithm using remotely sensed ground deformation products and locations of oil and gas fields as proxies for tectonic, hydrological and anthropogenic processes. The training model of a random forest algorithm that included 23 types of multidisciplinary datasets, including ground deformation, sedimentary basins, precipitation, soil moisture, topography, and hydrocarbon production fields succeeded in predicting 86%–95% of the representative data sets when applying the characterization algorithm.

Space Geodesy Program

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

NASA Space Geodesy Network

The NASA Space Geodesy Network (NSGN) stations continued to operate during the COVID-19 pandemic, maintaining or exceeding levels of scientific data output achieved in prior non-pandemic years. The backlog of pandemic-delayed repairs were addressed, including successful repairs of the Texas VLBI antenna cryogenics, Goddard VLBI antenna jack screw, and South Africa SLR station Mount Positioning and Controlling System. In 2021, the 7 NASA SLR station network tracked 111 different satellites delivering data for 180,703 satellite passes. The NASA VLBI stations participated in over 500 sessions making over 300,000 observations.

SGP continued to advance the next generation of VLBI (VGOS) by operating its broadband VLBI stations at Kōke'e Park Geophysical Observatory (KPGO) in Hawaii, Goddard Geophysical and Astronomical Observatory (GGAO) in Maryland, McDonald Geodetic Observatory (MGO) in Texas, and Westford in Massachusetts. The 2-station 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 a week session and demonstrated better performance than the legacy S/X Band VLBI Intensives. These VGOS intensive sessions are now producing operational products used by the IERS Rapid Service/Prediction Center at the U.S. Naval Observatory for the determination and prediction of the time-varying alignment of the Earth's terrestrial reference frame with respect to the celestial reference frame (i.e., Earth Orientation Parameters). The NASA VGOS stations routinely participate in 24-hr VLBI sessions with the international VGOS stations. These 24-hr VGOS sessions were incorporated into the 41-year (1979-2020) VLBI contribution to the realization of the 2020 International Terrestrial Reference Frame (ITRF2020). In 2022, we also initiated weekly Intensive sessions between MGO and the Wettzell observatory in Germany. The focus was to test improvements in scheduling strategies to improve the qualities of the VLBI Intensive observations. In addition, the objective was also to introduce another VGOS baseline for UT1 determination as a backup to the baseline KPGO-Wettzell, assuring operational robustness.

The development of the next-generation SLR systems for Texas, Maryland, and Svalbard advanced despite challenges from the pandemic. Facility work for all three sites was completed, including the installation of the telescope domes. The first Gimbal and Telescope Assembly successfully passed factory acceptance and was delivered and installed in the SGSLR facility at Goddard Space Flight Center. The build of the second Gimbal and Telescope Assembly was also completed and is scheduled for deployment to Svalbard in early 2023.

The NASA Satellite Laser Ranging (SLR) stations continue to provide precise tracking to an array of satellite targets, including science satellites in Low Earth Orbit (LEO) (such as GRACE-FO, IceSAT-2 Swarm A-B & C), satellites engaged in mapping using synthetic aperture radar (e.g. TerraSAR-X, Tandem-X and PAZ), as well as ocean radar altimeter satellites that monitor the changes in the ocean surface topography (such as Sentinel-6A/Michael Freilich, Jason-3, Sentinels 3A & 3B, Cryosat-2 & SARAL), geodetic spheres used for determination of the terrestrial reference frame and the determination of the time-variations in the low degree gravity field of the Earth (LAGEOS, LAGEOS-2, Starlette, Stella, LARES, Ajisai & Larets). NASA SLR stations will also provide support to the SWOT mission scheduled for launch later in 2022. NASA SLR stations are already tracking the LARES-2 mission, a geodetic sphere satellite launched by ASI (Italian Space Agency) to better estimate the Lense-Thirring effect, as a test of general relativity. We expect in the future LARES-2 will also contribute to the determination of the Terrestrial Reference Frame in the same way as LAGEOS & LAGEOS-2 do today.

JPL Geodetic Analysis Center

The JPL Geodetic Analysis Center has made progress on all fronts while still successfully producing and delivering a full suite of GPS analysis products and sustaining GipsyX Geodetic Data Analysis software for NASA and other researchers. Standard operations and progress on new development were made in spite of COVID-19, with personnel working from home for most of the year.

The transition from GPS-only to multi-GNSS operations was made with the start of operational production of Galileo + GPS orbit and clock products on October 1, 2021.

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. Efforts for the remainder of this year will be centered on further developing operations to regularly produce higher rate products. Four constellation GNSS solutions (GPS + Galileo + GLONASS + BeiDou) are produced daily as a research product and are compared to products from other GNSS analysis centers. 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 continued. Satellite Laser Ranging (SLR) data analysis capabilities are being used with GPS capabilities in TRF research with promising preliminary results. Very Long Baseline Interferometry (VLBI) capabilities are still in development and, when complete, these will be used with existing capabilities to analyze data from large multi-technique networks. The capability to analyze data from multi-technique networks is supporting a major research effort establishing terrestrial reference frame solutions. Investigation into applying some results of this research to improvements to operations GNSS products is also proceeding.

Terrestrial Reference Frame Combination

Effort this past year has centered on obtaining products describing technique specific network solutions from the Services of the International Association of Geodesy (IAG) and producing a Terrestrial Reference Frame (TRF) solution. The NASA/JPL approach to (JTRF) 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, and the solution is currently being analyzed and refined. Once validated, the JPL solution, "JTRF2020", will form the basis for regular updates, which are expected to begin in late 2023 and will be distributed on a publicly available website.

The NASA/GSFC VLBI analysis center coordinated the contribution of the VLBI technique to the next realization of the ITRF, (ITRF2020), using data from 1979-2020. The submission included 38 24-hr VGOS Sessions and two 24-hr "mixed-mode" tie sessions that tie together the legacy VLBI and VGOS networks. This is the first time VGOS data was used for the ITRF. The submission also included post-seismic deformation models that fit the VLBI data much better than ITRF2014.

The SGP supported University Of Maryland, Baltimore County SLR analysis center also coordinated the SLR contribution to ITRF2020 using observations to the LAGEOS, LAGEOS-2, and Etalon satellites from 1983 to 2021. The NASA/GSFC DORIS analysis center contributed to ITRF2020 by processing 27 years of data from 1992 to 2020 for 12 scientific satellites tracked by DORIS, including Jason-3. The new contribution is a 33%

improvement over previous submissions primarily due to a successful multi-year effort to characterize systematic errors in SLR data.

In addition, JPL is performing 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. An interim TRF solution determined by combining GPS data from ground stations, GPS data from well characterized LEO satellites, and Satellite Laser Ranging measurements from ground stations and spanning 5 years was produced and analyzed. The reference frame parameters compare favorably to those from ITRF2020, the international standard. Work over the next year will focus on expanding the time span of the experimental TRF solution and incorporating VLBI observations. The research is in its infancy but 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 32 currently required, and minimize the need for expensive ground stations, such as those required for SLR measurements.

SGP International and Interagency Cooperation

The NASA Space Geodesy Program (SGP) continues to be a key participant in the United States Delegation of the United Nations Committee of Experts on Global Geospatial Information Management's (UN GGIM) 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 an initial offer by Germany to host the Centre at the UN Campus in Bonn, and supported by a public GGIM Global Geodesy Forum. If successfully implemented, the Centre of Excellence will provide internationally funded staff for dedicated advocacy and assistance to nations wishing to invest in geodetic infrastructure and capacity development.

The IGS Central Bureau, managed by JPL, collaborated with other NASA Earth Science elements to contribute to the United Nations Global Assessment Report on Disaster Risk Reduction (GAR) an article about applications of GNSS observations for atmospheric hazard detection (wildfires, air quality). The GAR is a major biennial UN report addressing disaster risk reduction and acts as a high-level forum on sustainable development used by both regional and global organizations.

A collaboration of the IGS Central Bureaus and Global Differential GPS System (GDGPS), with consultation with international experts, proposed a use case for the Focus Group on AI for Natural Disaster Management. This group, based at the International Telecommunications Union in Geneva, Switzerland, chose the JPL GNSS-enhanced tsunami early warning proposal as a representative use case (i.e., natural disaster case studies). The proposal also provided visibility and recognition of the recent GDGPS analysis of GNSS measurements during the Hunga Tonga volcano eruption and resulting tsunami, demonstrating the utility of these measurements in a future tsunami warning system.

Global Positioning System Laser Retroreflector Array (GPS-LRA)

The SGP worked in cooperation with the United States Space Command and the United States Space Force to enable SLR to the GPS satellites. SLR to GPS will contribute significantly towards improving the accuracy and stability of the International and WGS84 Terrestrial Reference Frames, enabling a means to distribute this new accuracy uniformly to all systems utilizing GPS. SGP delivered an Engineering Qualification Model of the Laser Retroreflector Array (LRA) to the Space Force and the build of the first four flight units is underway. The first LRA equipped GPS satellite currently has an available for launch date in 2026. Report mentions on bottom of p10 that UAVSAR responded to 2 rapid response events but didn’t say what the utility of the instrument was to those events. If it was useful seems like something that should be highlighted.

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 new missions that are under construction (i.e. SWOT and NISAR), and identifying new and innovative techniques/technology that will allow us to ask the next generation of scientific questions that were not possible a few years ago, all within a limited budget profile. Below are highlights of WEC Focus Area funded research accomplishments that have matured in FY2022 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 a pair of cross-cutting publications that seek to characterize geophysical parameters that influence evapotranspiration (ET), a review paper that takes a look at the current state-of-the-art for data assimilation modeling, and a commentary on Open Source Science for hydrological sciences. 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 – Ecosystem / Evapotranspiration / Drought / Wildlife / Water Quality' describes new water related research that spans the hydrosphere and ecosphere.

Atmospheric humidity and soil moisture in the Amazon forest are tightly coupled to the region's water balance and the difference between two moisture fluxes, evapotranspiration and precipitation (ET-P). However, large and poorly characterized uncertainties in both fluxes, and in their difference, make it challenging to evaluate spatiotemporal variations of water balance and its dependence on ET or precipitation. Shi *et. al.* (2022, *Nature Communications*) found that satellite observations of the HDO/H2O ratio of water vapor are sensitive to spatiotemporal variations of ET-P over the Amazon. When calibrated by basin-scale and mass-balance estimates of ET-P derived from terrestrial water storage and river discharge measurements, the isotopic data demonstrate that rainfall controls wet Amazon water balance variability, but ET becomes important in regulating water balance and its variability in the dry Amazon. Changes in the drivers of ET, such as above ground biomass, could therefore have a larger impact on soil moisture and humidity in the dry (southern and eastern) Amazon relative to the wet Amazon.

Accurate evapotranspiration (ET) measurement over large scales with remote sensing can contribute to effective water resource management. However, ET measurement is challenging, particularly in complex agricultural landscapes. ET calculated with the water balance method using data from the Gravity Recovery and Climate Experiment (GRACE)/GRACE Follow-On (GRACE-FO) missions has been found to exceed estimates from land surface models, although there has been no definitive explanation. Pascolini-Campbell et. al. (2021, *Geophysical Research Letters*) found by using high resolution ET from ECOSTRESS, that this bias is attributed to fine-scale irrigation not captured by models but which mass conservation detects. The percentage of irrigated area scales linearly with the bias between observed and modeled ET ($R2 = 0.80$, $p < 0.01$). They estimate that irrigation drives 35% of summer evapotranspiration fluxes in a set of arid/semi-arid basins in the North American west and southwest.

Physics-based hydrological models are important in earth and environmental sciences thanks to their inherent capability of being applicable to the widest possible range of scales and environmental conditions. These models are increasingly being used to predict future water resources quantity and quality in response to climate and land use change, to monitor and assess hydroclimatic hazards (such as floods and droughts), and in general to understand the intertwined dynamics between the hydrological, atmospheric, and carbon cycles. Camporese and Girotto (2022, Frontiers in Water) describe the recent advance in Data Assimilation (DA), which refers to a suite of statistical techniques that incorporate observation data into mathematical models, with the goal of optimizing estimates of the system state (and possibly parameters). Data assimilation applications in integrated surface-subsurface hydrological models (ISSHMs) are generally limited to scales ranging from the hillslope to local or meso-scale catchments. This is because ISSHMs resolve hydrological processes in detail and in a physics-based fashion and therefore typically require intensive computational efforts and rely on ground-based observations with a small spatial support. At the other end of the spectrum, there is a vast body of literature on remote sensing data assimilation for land surface models (LSMs) at the continental or even global scale. In LSMs, some hydrological processes are usually represented with a coarse resolution and in empirical ways, especially groundwater lateral flows, which may be very important and yet often neglected. The authors review the recent progress in data assimilation for physics-based hydrological models at multiple scales and stress the need to find a common ground between ISSHMs and LSMs and outline a possible way forward to advance the use of data assimilation in integrated hydrological models.

Clark *et al.* (2021: *Water Resources Research*) make the case that open science is perhaps the most important paradigm shift in the recent history of scholarly publishing. They explore the challenges and opportunities associated with a possible transition of Water Resources Research to a publication model where all articles are freely available upon publication. The decision to convert to open access is framed by a mix of finances and values: who pays and how, and what will improve the affordability of publishing. The challenge is to increase the extent to which science is open and accessible. They propose that the next steps for the community will include an incisive analysis of the financial feasibility of different cost models, and weighing the financial burden for open access against the desire to further advance open science.

In keeping with these findings, the focus area has invested in two SnowEx hackweeks (July 2021 and 2022). These have been done with support from University of Washington's eScience institute and many members of the community. Organizers and teachers work before the Hackweek to organize SnowEx field campaign data and existing software tools to access said data. "Student" participation in the hackweeks is done through an open call to the community, and selection criteria include emphasis on broadening the diversity of those involved with SnowEx and THP. NASA's investment includes ensuring that participation is not limited to those than can financially afford in-person participation.

Water Budget and Water Cycle Dynamics

The bulk of WEC research activities focus on the characterization, quantification, and modeling of the different elements of the terrestrial water cycle: precipitation, snow, surface water, soil moisture, biological/ecosystem water, and groundwater. These activities include advancing science from our current missions (i.e. SMAP, GPM, MODIS, GRACE-FO, ECOSTRESS, Landsat) and new research supporting missions that are in development (i.e. SWOT and NISAR). Several WEC funded activities came to fruition with an updated accounting of the global water and energy budgets, leveraging many NASA investments to develop and produce individual variable data sets, from observations and reanalysis. Investments in these types of activities will enhance overall assessment through improved accounting of individual water budget/cycle terms. NASA is dedicated to global observations from spaceborne platforms. These investments align to support different stages of satellite mission development, data use, and societal benefit. This section 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. The following two publications highlight some of the snow related research followed by a description SnowEx dataset that are now publicly available.

Wang *et al.* (2022: *Remote Sensing*) addresses two technological obstacles related to satellite-based snow observations. Their analysis finds that 1100 km, 550 km, and 200 km are the minimum required swath width for a polar-orbiting sensor to meet snow-related applications demanding a 1-day, 3-day, and 30-day repeat cycles, respectively. The results of this paper provide valuable insights for potential future global snow missions. Wrzesien *et al.* (2022: *Journal of Hydrometeorology*), focused on the limitations of Land surface models (LSMs), commonly used to develop spatially distributed estimates of snow water equivalent (SWE) and runoff, but are limited by uncertainties in model physics and parameters, among other factors. The authors describe the use of model calibration tools to improve snow simulations within the Noah-MP LSM as the first step in an observing system simulation experiment (OSSE). Their findings show that calibration decreases domain averaged temporal root mean square errors (RMSE) and bias for snow depth from 0.15 to 0.13 m and from −0.036 to −0.0023 m, respectively, and improves the timing of snow ablation. Increased snow simulation performance also improves estimates of model-simulated runoff in four of six study basins, though only one has a statistically significant improvement.

Hojatimalekshah *et al.* (2022: Boise State) developed a dataset for use by the community to evaluate snow retrieval algorithms and perform snow hydrology research, which is a collection of 1m resolution snow depth, elevation, aspect, slope, canopy percent cover, canopy height, foliage height diversity (FHD) with 0.5 m, 1 m, and 2 m voxel sizes. They processed lidar data of Grand Mesa, Colorado, representing a data collection effort by the SnowEx campaign. Snow depth is computed by snow-off and snow-on dataset from September 2016 and February 2020, respectively. Snow-off lidar data were collected by the Airborne Snow Observatory (ASO), lidar system created by NASA/JPL. Snow-on lidar data are provided by Quantum Spatial as a part of the NASA SnowEx-2020 campaign.

Surface Water

WEC has invested in improving our ability to resolve surface water extent and measure river discharge, including preparing for the upcoming SWOT Mission. Both are important topics to pursue and to stay current with the advances in land modeling efforts that have moved from a traditional climate paradigm, which disregards horizontal movement of water, to one that models surface processes more comprehensively and at higher spatial resolutions. This advancement can facilitate the use of WEC observations to support carbon cycle research that focuses on resolving roles of surface water and rivers in the carbon budget. Furthermore, as we prepare for the SWOT and NISAR missions, and time-series data from GRACE-FO missions mature, technology and algorithm development are beginning to support new scientific advancements with increasing contributions in future GPRA cycles. WEC supports research that spanned a variety of surface water related science and technique development ranging from more comprehensive regional studies (i.e. Yukon and Mekong Rivers) to exploring new capabilities with NISAR and ICESat-2. Given that SWOT is anticipated to launch in 2022 we opted to focus on publications related to the mission and its prime hydrological foci, river discharge and surface water.

SWOT Science

The upcoming SWOT mission is expected to significantly increase our understanding of river flow rates in ungauged basins, and water storage in surface water reservoirs. A considerable amount of SWOT-related research has been funded in recent years in preparation for this mission. The following publications are a subset of the overall effort and focus on SWOT's measurement characteristics, temporal sampling for discharge, and the assimilation of SWOT data into hydrological models. In this section, we highlight a pair of publications that seek to better understand SWOT discharge measurements and how these measurements may improve regional discharge estimates. We also highlight a paper that looks at potential challenges facing SWOT's algorithms targeting lake/reservoir surface water extent.

Remote sensing approaches provide a platform for detecting and tracking changes in the surface water extent of the world's lakes and reservoirs on a global scale. The following two publications use different approaches to resolve trends and drivers associated with changes in surface water. Birkett *et al.* (2022: *Journal of Great Lakes Research*) expanded and enhanced two data sets: GREALD, the large (surface area $\geq$100 km^2) lake and reservoir database and GELD, ephemeral lakes (area $\geq$100 km^2). They found that with altimetric repeat visit times of 10-day to monthly, at least 80% of the permanent water bodies ($\geq$10 km^2) have been overflown at some period since the 1990s. Current information on water use and reservoir formation date show that the primary use of the reservoir class is hydroelectric power, and that China, Brazil, India, Turkey, and Vietnam dominate the dam building in recent decades. Bonnema *et al.* (2022: *Geophysical Research Letters*) utilized satellite synthetic aperture radar (SAR) data to estimate surface area variations in a set of the world's largest lakes and reservoirs. They found that the total surface area variability was relatively small when aggregated globally, only accounting for 2% of mean global surface water area. However, the total shoreline area that transitioned between water and land as a result of lake and reservoir variability was much more substantial, around 20% of mean global surface area. The variability of smaller water bodies contributed more to these transitional areas than larger water bodies. They also found that artificial reservoirs tended to be more variable than similarly sized natural lakes. Ultimately, the large surface area variations evidenced here, particularly in small water bodies, could have a previously underappreciated impact on the Earth System. Collectively, these approaches are enabling new research to better understand the drivers of water level changes in our global lakes and reservoirs.

Altenau *et al.* (2021: *Water Resources Research*) introduces the SWOT River Database (SWORD), which will serve as the framework for the SWOT river vector products consisting of river reaches (∼10 km long) and nodes (∼200 m spacing within reaches). SWOT will provide unprecedented observations of river water surface elevation, width, and slope. Because rivers are dynamic features that change frequently, the vector product will allow scientists to analyze the data most effectively if the SWOT observations are attached to an existing database that is static in space and time. SWORD contains a total of 213,485 reaches (~10km long) and 10.7 million nodes (~200m spacing within reaches). When defining river reaches, this database can serve as a framework for modeling river flows at global scales and for conducting large-scale hydrologic analyses using ground measurements and/or additional satellite observations.

Riggs *et al.* (2022: *Environmental Modeling & Software)* presented RODEO, an algorithm for estimating river discharge using Landsat observations in near-real time. RODEO is validated with 456 gauges and uses a novel quantile rating curve technique that pairs Landsat river widths with discharge estimates from a global hydrologic model. RODEO also characterizes the uncertainty of river discharge (RSQ) estimates (estimated rms error ~7%), enabling RSQ retrievals to be used for data assimilation into hydrologic and streamflow models. The RODEO algorithm is implemented as a freely available, off-the-shelf cloud-based Google Earth Engine application that provides RSQ estimates across North America from 1984-present. These will provide more robust context in which to interpret SWOT observations by allowing users to look both at conditions in previous years and farther upstream, in areas too narrow to be measured by SWOT, but that flow into SWOT observed river reaches.

Many sensors are suitable for accurate delineation of open water extent, but in vegetated environments, the vegetation canopy can obscure the presence of standing water from detection. Detecting inundation extent in these vegetated environments is especially critical for identifying flooding extent where surface water may exceed flood boundaries and extend into forests surrounding nearby lakes and streams. Regular and timely observations of water surfaces by optical sensors can be impeded by both cloud cover and vegetation. In Chapman *et al.* (2022: *Applied Earth Observations and Remote Sensing*), two microwave techniques for identifying inundation extent are investigated and compared: *L*-band global navigation satellite systems reflectometry (GNSS-R) and *L*- and *C*-band synthetic aperture radar (SAR); The paper confirms that there are correspondences between metrics derived from GNSS reflected signals and *L*-band SAR to inundated area, including wetlands covered by vegetation. The study also found that the higher spatial resolution CYGNSS raw IF data provided a more accurate representation of inundated area than from

CYGNSS L1 SNR, that would increase the number of potential applications of CYGNSS data, if more downlink capability were available.

Russo *et al.* (2021: *IEEE Transactions on Geoscience and Remote Sensing*) developed a novel metric for detecting coherence in global navigation satellite system reflectometry (GNSS-R) signals. Their approach applies the Von Neumann information entropy metric for density matrices, a powerful indicator of the degree of mixing between states, coherent and incoherent, of the scene under investigation. The metric is applied to a set of raw Intermediate Frequency data acquired by the cyclone global navigation satellite system (CYGNSS) observatories over Lake Okeechobee FL, to test the sensitivity of the entropy to different land cover types, including wetlands and open water. Visual comparison of results with Sentinel-1 images provides a first step in the validation of the effectiveness of entropy in detecting the presence of water covered by emergent vegetation. The results justify further study on the ability to discriminate among different types of vegetation coverage. In addition, the entropy-based metric could be implemented on future space-based GNSS-R receivers to adapt the incoherent integration times to the observed scene, thus achieving an improvement in along-track resolution.

High Mountain Asia

The Himalayan mountain glaciers encompass the largest reservoirs of freshwater on Earth outside of the polar regions. The melting of snow and glaciers in High Mountain Asia (HMA) contributes up to 70% of the annual water supply of over 1.4 billion people in the region. In 2015, NASA formed the High Mountain Asia Science Team (HiMAT) as an interdisciplinary science team that focused on studying glaciers, snow, permafrost, and precipitation to improve our understanding of regional changes, water resources, and induced impacts, while furthering NASA's strategic goals in Earth system science and societal applications. The second HiMAT was selected and began new research in the spring of 2021 because the High Mountain Asia continues to be an important research theme.

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 snow patterns in HMA despite relatively short periods of record. Ackroyd *et al.* (2021: *Frontiers in Earth Science*) assessed trends in snow cover duration using MODIS between 2002 and 2017 across the headwaters of the region's primary river basins (Amu Darya, Brahmaputra, Ganges, Indus, and Syr Darya) using fractional snow cover duration (fSCD) calculated on both annual and monthly time scales. They found that snow cover is in decline, which is most pronounced in elevation bands where snow is most likely to be present and most needed to sustain glaciers. Some of the strongest negative trends in fSCD were in the Syr Darya, which has 13 fewer days between 4,000–5,000 m, and Brahmaputra, which has 31 fewer days between 5,000–6,000 m. The only increasing tendency was found in the Indus between 2,000 and 5,000 m.

Glacier melt is a major water sources in HMA and downstream. Giese et al. (2022: Frontiers in Earth Science) found that while glacier melt discharge tends to be large where there are more glaciers, modeling reveals that glacier melt does not scale directly with glaciated area. Elevation can play a role. Further, regional-level application of the model allows an assessment of the dominant drivers of melt and their spatial distributions. As this study provides a theoretical exploration of the spatial patterns to glacier melt in the Upper Indus Basin–a critical foundation for understanding when glaciers melt–this information that can inform projections of water supply and scarcity in Pakistan, a country heavily dependent on the Indus River, which is vulnerable to changes in climate.

As atmospheric warming intensifies glacier melting and glacial-lake development in High Mountain Asia (HMA), this could increase glacial-lake outburst flood (GLOF) hazards and impact water resources and hydroelectric-power management. Chen *et al.* (2021: *Earth System Science Data*) developed a HMA glacial-lake inventory (Hi-MAG) database to characterize the annual coverage of glacial lakes from 2008-2017 at 30 m resolution using Landsat satellite imagery. The data show that glacial lakes exhibited a total area increase of 90.14 km^2 in the period 2008–2017, a +6.90 % change relative to 2008. The annual increases in the number and area of lakes were 306 and 12 km^2, respectively, and the greatest increase in the number of lakes occurred at 5400 m elevation, which increased by 249. Their results demonstrate that proglacial lakes are a main contributor to recent lake evolution in HMA, accounting for 62.87 % of the total area increase.

Rounce *et al*. (2021: *Geophysical Research Letters*) addresses the gap in knowledge that global glacier models do not account for the debris layer (e.g., boulders, rocks, and sand) because the debris thickness is unknown despite most glaciers containing debris covering the underlying ice over much of the surface. Their study provides the first estimates of debris thickness for debris-covered glaciers globally and shows that debris substantially reduces regional glacier mass loss. In addition, they find that recent observations that debris-covered and clean ice glaciers are thinning at similar speeds is primarily due to differences in how glaciers flow. These results fundamentally advance the ability to account for debris in glacier reconstructions, landscape evolution models, hazard assessments, and glacier projections of glacier runoff and their contribution to sea-level rise.

Mishra *et al.* (2021: *Frontiers in Water*) describes in “Grand challenges of hydrologic modeling for food-energy-water nexus security in High Mountain Asia,” “Climate-influenced changes in hydrology affect water-food-energy security that may impact up to two billion people downstream of the High Mountain Asia (HMA) region.” However, knowledge gaps in such areas as understanding of the spatial and temporal variations in climate, surface impurities in snow and ice such as black carbon and dust that alter surface albedo, and glacier mass balance and dynamics create challenges in predicting where and when the impact of changes in river flow will be the most significant economically and ecologically. The HiMAT framework could be applied to develop scientific understanding of spatio-temporal variability in water availability and the resultant downstream impacts to support water resource management under a changing climate regime.

Given the terrain, the elevation, and fragility of the landscape, the High Mountain Asia region experiences and is susceptible to many hazards. A pair of publication highlight HMA region’s vulnerabilities to glacial lake outburst floods (GLOF) and avalanches.

Taylor et al. (2022: *Journal of Glaciology*) focused on supraglacial ponds and ice cliffs in the region between Bhutan and Tibet and better understanding of their spatial distribution and evolution due to high ice loss rates and GLOF vulnerabilities. Using high-resolution Planet Labs satellite imagery, the team provides the first short-term, high-resolution dataset of supraglacial pond and ice cliff evolution for three glaciers along the Bhutan–Tibet border from 2016 to 2018. A total of 5754 ponds and 2088 ice cliffs were identified. On average, ~19% of the total number of ponds had a coincident ice cliff. Pond spatial distribution was driven by ice-surface velocities, with higher numbers of ponds found in areas of low velocity. This detailed study provides a framework for future monitoring in this important region of the Himalayas.

February 7th, 2021, a large rock-ice avalanche triggered a debris flow in Chamoli district, Uttarakhand, India, leaving hundreds dead or missing. Van Wyk de Vries et al. (2021: *Natural Hazards and Earth System Sciences*) assess the precursory signs exhibited by this steep slope prior to the catastrophic collapse and evaluate monthly slope motion from 2015 to 2021 through feature tracking of high-resolution optical satellite imagery. They found from analysis of pre- and post-event DEMs that the 26.9 m^3 collapse block moved over 10 m horizontally and vertically in the five years preceding the collapse, with particularly rapid motion occurring in the summers of 2017 and 2018. The analysis suggests that the collapse resulted from a combination of snow-loading in a deep headwall crack and permafrost degradation in the heavily jointed bedrock. While a clear precursory signal highlights the potential of satellite imagery for monitoring the stability of high-risk slopes, the timing of the Chamoli rock-ice avalanche could likely not have been forecast from satellite data alone.

Soil Moisture

Soil moisture is the vital connector between surface water and groundwater, and it influences precipitation runoff, snowmelt volumes, and many fluvial hazards. Soil moisture is also the interface between water and plants for many ecosystems making it an important connection between the water, energy, and carbon cycles. The launch of SMAP in 2015 made it possible to begin to address global soil moisture issues at greater detail. Similarly, as algorithms improve for analyzing GRACE data, it is becoming possible to better characterize soil moisture contributions to GRACE time-series data. The highlighted publications below focus on improving and expanding soil moisture measurements made from SMAP and CYGNSS.

Passive microwave remote sensing technology is effective at resolving soil moisture on a global scale with product resolution that are tens of kilometers per measurement, but at these resolutions it is not viable to characterize soil moisture (SM) variability on a regional scales. Fang *et al.* (2022: *Vadose Zone Journal*) developed a downscaling algorithm based on the thermal inertia theory–derived relationship between soil moisture and temperature difference using outputs from the Global Land Data Assimilation System–Noah Land Surface Model and the land long-term data record–Advanced Very High Resolution Radiometer normalized difference vegetation index (NDVI) dataset and applied to the Aqua MODIS land surface temperature/NDVI data to produce a downscaled 1-km Soil Moisture Active Passive (SMAP) radiometer daily SM product on a global scale from 2015 to 2020. They found that the downscaling model performs better in the middle or low latitudes than in high latitudes. It also performs better in warm months than in cold months. Theoretically, one kilometer resolution SM data is more useful for both science investigations and decision makers, such as those in the agricultural and water resources sectors, though how useful will have to be the subject of further studies.

Soil moisture is very sensitive to drought and can be an indicator of a flash drought. Sehgal *et al.* (2021: *Water Resources Research*) used SMAP data to develop a new method for near-real-time characterization of droughts by a non-linear combination of Soil Moisture Stress (i.e. drought stress) and Relative Rate of Drydown (drought stress intensification rate) for a new parameter called Flash Drought Stress Index (FDSI) that can identify emerging flash droughts (FDSI $\geq$ 0.71 for moderate to high RRD and SMS). Globally, FDSI shows a high correlation with concurrent meteorological anomalies. They found that about 5.6% of the earth's landmass experienced flash droughts of varying intensity and duration during 2015–2021 (FDSI $\geq$ 0.71 for >30 consecutive days), majorly in global drylands. FDSI shows high skill in forecasting vegetation health with a lead of 0–2 weeks, with exceptions in irrigated croplands and mixed forests.

Accurate and timely quantification of near-surface soil moisture is important for many hydrologic and atmospheric applications. The upper few cm of the soil constitutes the boundary between the land surface and the atmosphere, and the relative partitioning between sensible and latent heat fluxes is governed by the moisture content of the soil. Roberts *et al.* (2022, *Remote Sensing*) use a deep-learning convolutional neural networks approach to determine complex relationships between the reflection GNSS measurements (GNSS-R) from CYGNSS and surface parameters, thereby providing the groundwork for a mechanism to achieve improved global soil moisture estimates. They found that their Deep-Learning GNSS-R approach performed well when compared with SMAP and provided higher spatial and temporal resolution capabilities. They also note that there is a potential for their approach to yield improved accuracy and coverage compared to existing techniques for soil moisture using CYGNSS 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) measures the surface deformation associated with the natural anthropogenic withdrawal and recharge/injection of water. Water volume is then obtained by modeling the surface deformation. Data from GRACE and GRACE-FO provides global measurements of mass change, including the redistribution of water (solid and liquid). Both techniques measure changes in water storage and not the absolute volume. This section contains five papers that exploited these while using other observations and model output, to reveal important findings about the natural and human-influences on groundwater variations and its interaction with the rest of the global water cycle. These are followed by two additional papers that are continuing to improve upon these approaches by incorporation of SMAP and other data sets.

Following extreme drought during the 2019-2020 bushfire summer, the eastern part of Australia suffered from a week-long intense rainfall and extensive flooding in March 2021. To quantify prompt water storage changes associated with the 2021 March flooding, Han et al. (2021: *Earth and Space Science*) processed the low-latency (1-3 days), high-precision intersatellite laser ranging measurements from GRACE Follow-On spacecraft and determined instantaneous gravity changes along spacecraft orbital passes. Such new data processing detected an abrupt surge of water storage approaching 60-70 trillion liters (km3 of water) over a week in the region, which concurrently caused land subsidence of ~5 mm measured by a network of ground GPS stations. This was the highest speed of ground water recharge ever recorded in the region over the last two decades. Compared to the condition in February 2020, the amount of recharged water was similar but the recharge speed was much faster in March 2021. While these two events together replenished the region up to ~80% of the maximum storage over the last two decades, the wet antecedent condition of soils in 2021 was distinctly different from the dry conditions in 2020 and led to generating extensive runoff and flooding in 2021. Understanding these variations and magnitudes of water storage changes in response to these climate extremes is critical for developing timely water management strategies.

Panda *et al.* (2022: *Earth's Future*) analyzed observations from ~15,000 groundwater monitoring wells and the Gravity Recovery and Climate Experiment satellites together with irrigation, agricultural, and meteorological datasets to show how drought-induced coupling between natural and anthropogenic groundwater storage variations has caused sustainability challenges in India, the world's biggest consumer of groundwater for irrigation. Notably, the mechanisms and consequences of such coupling differ significantly depending on aquifer types. In Andhra Pradesh's hard rock aquifer, groundwater declines have been limited, despite the nearly constant water scarcity that its farmers face. In West Bengal's highly permeable alluvial aquifer, the water table is declining rapidly (15 cm/yr) due to a policy that encourages irrigation. Situated between these two states, Odisha's aquifer shows substantial resilience to drought, owing to the state's relatively natural landscape and forest restoration policy. The findings of this study provide new insights to understand the divergent aspects of groundwater irrigation in north versus south India, which can enable development of adaptation and mitigation strategies to avert the looming water crisis. These insights are made possible by satellite observations that compensate for inadequate water usage reporting and limited information on irrigation practices.

Similarly, regions in Lebanon with high productivity of agriculture, such as the Beqaa Plain, often rely on groundwater supplies for irrigation demand. Recent reports have indicated that groundwater consumption in this region has been unsustainable, and quantifying rates of groundwater depletion has remained a challenge. Massound *et al.* (2021: *Remote Sensing*) utilize 15 years of data (June 2002–April 2017) from GRACE to show Total Water Storage (TWS) changes in Lebanon's Beqaa Plain. To disentangle the TWS signal and calculate groundwater storage changes, the study used complementary information on hydrologic cycle variables, such as soil moisture storage, snow water equivalent, and canopy water storage from the Global Land Data Assimilation System (GLDAS), and surface water data from the largest body of water in the region, the Qaraaoun Reservoir. They determined that the majority of the losses in TWS are due to groundwater depletion in the Beqaa Plain. Results show that the rate of groundwater storage change in the West Beqaa is nearly +0.08 cm/year, in the Rashaya District is −0.01 cm/year, and in the Zahle District the level of depletion is roughly −1.10 cm/year. Results were confirmed using Sentinel-1 interferometric synthetic aperture radar (InSAR) data, which provide high-precision measurements of land subsidence changes caused by intense groundwater usage. Furthermore, data from local monitoring wells showcase the significant drop in groundwater level that is occurring through much of the region. This study also demonstrates the value of data from remote sensing to compensate in areas where (in situ) groundwater measurements are lacking.

Subsidence induced by groundwater depletion is a grave problem in many regions around the world, leading to a permanent loss of groundwater storage within an aquifer and even producing structural damage at the Earth's surface. California's Tulare Basin is no exception, experiencing about a meter of subsidence between 2015 and 2020. However, understanding the relationship between changes in groundwater volumes and ground deformation has proven difficult. Vasco *et al*. (2022: *Scientific Reports*) employed surface displacement measurements from InSAR and gravimetric estimates of terrestrial water storage from GRACE to characterize the hydrological dynamics within the Tulare basin. The removal of the long-term aquifer compaction from the InSAR time series reveals coherent short-term variations that correlate with hydrological features. For example, in the winter of 2018–2019 uplift is observed at the confluence of several rivers and streams that drain into the southeastern edge of the basin. These observations, combined with estimates of mass changes obtained from the orbiting GRACE satellites, form the basis for imaging the monthly spatial variations in water volumes. This approach facilitates the quick and effective synthesis of InSAR and gravimetric datasets and will aid efforts to improve our understanding and management of groundwater resources around the world.

California's Central Valley aquifer is a critical freshwater resource for the state, providing drinking water to 6.5 million residents and irrigation water for more than half of the nation's produce. Yet, many regions within the Central Valley lack groundwater monitoring wells or continuous well data, rendering in situ monitoring challenging, and potentially preventing adequate sustainability plans, now required by the state of California under its Sustainable Groundwater Management Act (SGMA). To address this gap, Kim et al (2021: *Journal of the American Water Resources Association*) demonstrated that when combined with other data, GRACE and GRACE Follow-On provide valuable information about groundwater storage changes at a subbasin scale. Additionally, InSAR measurements can map land subsidence, and GPS can be used to estimate crustal uplift. The study was able to overcome the challenge that all these measurements have different resolutions, coverages, discretization and record length to assess and document the utility of the composite dataset to be a suitable resource for the SGMA-related analysis.

Two additional studies furthered knowledge of soil moisture, groundwater hydrology, and the ability to measure groundwater. The Soylu *et al*. (2022: *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*) paper on "Global shallow groundwater patterns from soil moisture satellite retrievals" seeks to address the gap of global scale, high spatiotemporal resolution groundwater observations due to the hindrance caused when shallow groundwater has a direct impact on surface soil moisture. The authors estimate the spatial and temporal distributions of shallow groundwater-influenced areas at a global scale by training an ensemble machine learning algorithm, using outputs from a variably saturated soil moisture flux model, to identify the shallow groundwater occurrence. The overall accuracy of the algorithm in reproducing the soil moisture flux model results was 95.5%. Then, the authors applied the algorithm to spaceborne soil moisture observations retrieved by SMAP to present a global-scale shallow groundwater map derived from the SMAP observations. The derived global distribution of shallow groundwater identifies wetlands, large riparian corridors, and seasonally inundated lowlands. The results showed that 19% of terrestrial land cover had been influenced by shallow groundwater at some point in time during the period of interest (2015–2018). Indeed, SMAP observations can be used in estimating shallow groundwater in high spatiotemporal resolution at a global scale, potentially providing invaluable inputs for modeling and environmental monitoring studies.

Massoud *et al.* (2022: *Hydrology and Earth System Sciences*) by on "Information content of soil hydrology in a west Amazon watershed as informed by GRACE," the authors quantitatively characterize the capability of GRACE measurements – a key constraint on total water storage (TWS) – to inform and constrain these processes. The research further quantifies information gain with regard to terrestrial water states, associated fluxes, and time-invariant process parameters. The data-constrained terrestrial water storage model can capture basic physics of the hydrologic cycle for a watershed in the western Amazon during the period January 2003 through December 2012, with an r2 of 0.98 and root mean square error of 30.99 mm between observed and simulated TWS. Furthermore, the findings show a reduction of uncertainty in many of the parameters and state variables. The annual and interannual variability of the system are also simulated accurately. Cumulatively, the results suggest the potential of using gravimetric observations of TWS to identify and constrain key parameters in soil hydrologic models.

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

WEC seeks to better understand the two-way interactions between the hydrosphere and ecosphere. The availability of water for life encompasses the water supply, which includes the timing, magnitude, duration, and storage capabilities of the water (groundwater, soil moisture, surface water, snow, ice melt), as well as the water quality and the influence of water on the geomorphology. The vegetation water content of ecosystems is a living water reservoir which contributes to moving water through the global water and energy cycles through evapotranspiration (ET). Furthermore, anthropogenic activities such as agriculture production contribute to the movement of water through the global water budget and energy cycles.

Wildlife and Water

Animals are often on the move, searching for the essentials they need to survive. One of these essentials is of course water. But aside from using water to drink and wash, water in other stages of the water cycle can also impact wildlife. The following publications look at changes in water availability on fish.

Estuaries, and the fish who lives there, worldwide are experiencing stress due to increased droughts, often prompting intervention by environmental managers and government agencies. Ade *et al.* (2021: *Journal of the American Water Resources Association*) assess fish habitat and the effects of an emergency drought barrier on estuarine turbidity using satellite remote sensing to derive of turbidity maps time series that: (1) identify favorable turbidity conditions for the endangered fish species, delta smelt (Hypomesus transpacificus), during the height of the great California drought in the dry season of 2015, and (2) evaluate changes in turbidity following the installation of an emergency saltwater intrusion barrier. They found that several persistent areas of turbidity refugia throughout the summer in the north and west Delta; however, there was infrequent connectivity. This research can contribute to effective management of water resources in estuarine systems by demonstrating how new technologies and methodologies can support decision-making processes.

Gustine *et al*., (2022: *IEEE Transactions on Geoscience and Remote Sensing*) focused on the endangered delta smelt in the San Francisco Estuary and Sacramento–San Joaquin River Delta (Bay Delta) by investigating the relationship between open water surface and subsurface conditions from spaceborne thermal measurements (ECOSTRESS and Landsat-8) and in situ sensor data from the California Data Exchange Center to produce estimates of spatially continuous bulk temperature. They found that ECOSTRESS and Landsat-8 surface temperature measurements are well-correlated with bulk water temperatures. ECOSTRESS surface temperatures also were warmer than bulk temperatures in the midday period and cooler in the morning and evening periods. They also found that across the Bay Delta, including open waters and pelagic bays, temperature conditions causing stress and mortality for the Delta Smelt were persistent throughout the day during summer months.

The last paper looking at the delta smelt in California from Halverson *et al*. (2022: *Environmental Science & Technology*) uses Landsat 5, 7, and 8 level 2 collection 2 surface temperature to examine habitat suitability conditions spanning 1985–2019, relative to the thermal tolerance of the endemic and endangered delta smelt and two non-native fish, the largemouth bass and Mississippi silverside in the upper San Francisco Estuary. Thermally unsuitable habitat, indicated by annual maximum water surface temperatures exceeding critical thermal maximum temperatures for each species, increased by 1.5 $km^2\ yr^{-1}$ for the delta smelt with an inverse relationship to the delta smelt abundance index from the California Department of Fish and Wildlife. Regression analysis showed that the delta smelt are unable to thrive when the thermally unsuitable habitat exceeds 107 km^2. A habitat unsuitable for the delta smelt but survivable for the non-natives is expanding by 0.82 $km^2\ yr^{-1}$. Thus, warming waters in the San Francisco Estuary are reducing the available habitat for the delta smelt.

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 papers explore these complications associated with coastal waters.

The Coronavirus disease 2019 (COVID-19) pandemic halted human activities globally in multiple sectors including tourism. As a result, nations with heavy tourism, such as Belize, experienced improvements in water quality. Callejas *et al*. (2021: *Frontiers in Marine Science*) used MODIS imagery to assess the impact that halted tourism activity related with the COVID-19 pandemic had on improvements in water quality in countries with a significant tourist industry. They developed monthly composites for two periods, 2002–2019 (baseline) and 2020 and found that through the shutdown period that the water quality indicator was lower in 2020 at high traffic areas, but not for low traffic areas. After an unusually active hurricane season in 2020, the researchers observed decreased water clarity along the entire coast of Belize. This study provides proof of concept that satellite-based monitoring of water quality can complement in situ data and provide evidence of significant water quality improvements due to the COVID-19 shutdown, likely due to reduced marine traffic.

Harringmeyer *et al*. (2021: *Frontiers in Environmental Science*) took advantage of a 6-week wastewater diversion event in Santa Monica Bay, California in 2015 and the availability of Portable Remote Imaging SpectroMeter (PRISM) imagery acquired during the diversion to assess if UV-visible imaging spectroscopy could facilitate the detection of chromophoric dissolved organic matter (CDOM) and help differentiate wastewater effluent-derived CDOM from other sources. They found that a comparison of local empirical algorithms with varying amounts of spectral information implemented on PRISM data showed that incorporating UV remote-sensing reflectance (Rrs) as a predictor significantly improved retrieval of CDOM absorption coefficients. Optimal performance was reached when combining Rrs(365), Rrs(400), and Rrs(700) as predictors of CDOM absorption coefficients in a multiple linear regression, however, using the entire UV-visible spectrum (365–700 nm) in a partial-least-squares regression (PLSR) did not improve retrievals, indicating that a few carefully chosen predictors in the UV-visible domain were sufficient to empirically differentiate CDOM from phytoplankton in coastal waters minimally influenced by sediments or bottom reflectance.

Our final paper evaluating water quality in urban deltas investigated water quality conditions in the San Francisco Estuary and its upstream Sacramento–San Joaquin River Delta. Lee *et al*. (2021: *Journal of the American Water Resources Association*) used Sentinel-2A/B remotely sensed observations to evaluate patterns in turbidity during the Suisun Marsh Salinity Control Gates Action (“Gates action”), a pilot study designed to increase habitat access and quality for the endangered Delta Smelt. Their basic strategy was to direct more freshwater into Suisun Marsh, creating more low salinity habitat that would then have higher (and more suitable) turbidity than upstream river channels. For all seven acquisitions evaluated in a 3 month period in 2018, turbidity conditions in Bays and Sloughs subregions were consistently higher (and more suitable) than what was observed in the upstream River region. This overall pattern was observed when comparing images acquired during similar tidal stages and heights.

<u>Section 1.1.8.6</u> 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**, the 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. 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 WADFA's support of the new Open Source Science Initiative (OSSI), both CHIRP and CLIMCAPS are made freely available in the AWS cloud.

In 2020, WADFA started a NASA-NOAA joint Earth science Research from Geostationary Operational Satellite Systems as our partial fulfillment of the 2017 Decadal Survey: "Enabling Untapped NASA-NOAA Synergies." NOAA's GOES-R geostationary satellite observations have been used in creating climate data records, characterizing convective storms, and monitoring environmental changes. WADFA is highlighting selected research results from the geostationary satellites.

In this time period, WADFA also ran two field campaigns: IMPACTS and CPEX-AW. While IMPACTS is an EV3 mission, CPEX-AW is a campaign directly funded by WADFA, focusing on atmospheric winds measurement. These activities are reported at the end of this section.

<u>Characterizing the Behavior of the Atmosphere:</u>

<u>Hyperspectral Infrared Radiance Climate Records</u>: The calibration of the Cross-track Infrared Sounder (CrIS) radiance record continued this year at the Goddard Earth Sciences Data and Information Services Center (GES DISC) with significant adjustments to the algorithm due to the switch from Side-1 to Side-2 electronics and different Neon calibration lamps in order to retain climate-level radiance calibration. The CHIRP (Strow

et. al. 2021) combines Atmospheric Infrared Sounder (AIRS) radiances with those from the CrIS series of sensors into a single homogeneous (common spectral response with instrument bias offsets removed) radiance record. The nearly 20-year CHIRP climate radiance data record was migrated to the GES DISC Amazon Web Services (AWS) cloud this year where it is continuously updated, providing users with "in-place" access for scientific analysis. Making the data set available in the public cloud will allow open access to NASA's data, encourage open collaboration, reduce the effort in staging data for research, and enable more streamlined data analysis thus increased scientific research throughput.

Multi-Platform, Multi-Instrument Long-term Sounding Record: In 2021, CLIMCAPS V2.0 became publicly available at GES DISC for all three platforms: Aqua (AIRS and Advanced Microwave Sounding Unit [AMSU]), Suomi National Polar-orbiting Partnership (SNPP), and Joint Polar Satellite System-1 (JPSS-1) (CrIS and Advanced Technology Microwave Sounder [ATMS]). There has been a strong response from various sectors of the end user community. It is worth listing a few of the new, developing applications here to highlight the value of a sounding product like CLIMCAPS. These include the assimilation of CO and O_3 into GEOS-Chem, the inclusion of CLIMCAPS tropospheric O_3 into the Tropospheric Ozone Assessment Report (TOAR) 2.0, derivation of 3D winds from CLIMCAPS H_2O profile retrievals (Ouyed et al., under review), and interest in continuing the long-term record of derived Outgoing Longwave Radiation (OLR). Efforts to respond to and support this fast-growing community include direct exchanges, documentation in the form of science application guides, and web-based code and tools (Smith et al., 2021). The release of the full record of CLIMCAPS V2.0 via the GES DISC AWS cloud service in 2022 adds another important avenue for engaging with the scientific and operational communities. CLIMCAPS is one of the first NASA products that GES DISC migrated to the AWS cloud because of the strong interest in this sounding record. In addition to atmospheric profiles, CLIMCAPS retrieves cloud top pressure and cloud fraction. Clouds present the biggest source of uncertainty in atmospheric soundings from infrared measurements. In addition to quantifying scene complexity, these cloud parameter retrievals add value to cloud observations from imagers, such as Moderate Resolution Imaging Spectroradiometer (MODIS), Visible Infrared Imaging Radiometer Suite (VIIRS), and Advanced Baseline Imager (ABI), especially for high cirrus clouds. Scientists are characterizing cloud observations from these different instruments (e.g., Yue et al., 2022) to lay the groundwork for developing a multi-instrument cloud product that more accurately characterizes cloud amount and structure. There is the ability to maintain the National Oceanic and Atmospheric Administration (NOAA) Unique Combined Atmospheric Processing System (NUCAPS) as part of CLIMCAPS because they share sections of the NASA AIRS Science Team source code. In 2022, a non-operational version of NUCAPS for Aqua, using AIRS Level 1B files received from direct broadcast stations and delivered to the Advanced Weather Interactive Processing System (AWIPS-II) in real-time via a local area network, has been produced. At the NOAA Hazardous Weather Testbed, forecasters were able to evaluate soundings from Aqua in their native decision-making environment. This was also the first year that weather forecasters used satellite soundings to characterize the evolution of weather systems from two different platforms/instruments and within 50 min of each other.

Single Field-of-View Sounder Retrievals: The Single Field-of-view Sounder Atmospheric Products (SiFSAP) were used to study stratosphere to troposphere (STT) transport and cold air outbreaks (CAO). The SiFSAP temperature, water vapor, and O_3 profiles derived from the CrIS onboard SNPP, with a high horizontal resolution of approximately 14 km, provide a prominent opportunity to examine STT transport (Xiong et al., 2022a). In Xiong et al. (2022b), the SiFSAP atmospheric profiles have also been used to study an extreme CAO episode that occurred on January 27-31, 2019 across much of the United States Midwest. These publications demonstrate the value of SiFSAP retrieval products for STT and CAO dynamic transport studies and for Numerical Weather Prediction (NWP) reanalysis model evaluations.

AIRS Observes Atmospheric Waves Created by Hunga Tonga Volcanic Eruption: A Nature news article, published January 18, 2022 (Adam, 2022), features atmospheric waves created by the recent Tongan volcanic eruption, as revealed by AIRS data and imagery. The unusual patterns of gravity waves were discovered in AIRS images taken in the hours after the large and explosive eruption of the Hunga Tonga–Hunga Haʻapai volcano on January 14. The wave patterns, with dozens of concentric circles stretching over a vast region, and a mixture of wave sizes and types, are unlike anything seen after previous volcanic events in the almost 20-year AIRS data record. The Hunga Tonga-Hunga Ha'pai volcanic eruption was one of the most explosive of the modern era and triggered an unprecedented range of atmospheric gravity waves. These gravity waves were observed by instruments, including AIRS in the stratosphere and Aeronomy of Ice in the Mesosphere (AIM) Cloud Imaging and Particle Size (CIPS) in the mesosphere (Wright et al., 2022). Simulating gravity waves generated by the eruption provides insights into the strengths and deficiencies of atmospheric models. This study was only possible by combining observations from multiple instruments and platforms. This use of AIRS and AIM CIPS data is an excellent example of the synergy between NASA's Earth Science (AIRS) and Heliophysics (AIM) divisions.

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 (SDR) Fully Developed Seas 10 meter–referenced neutral stability-equivalent wind speed (FDS). An updated version (v3.1) was released in 2021 (CYGNSS, 2021). It incorporates new corrections for the sensitivity of the CYGNSS radar measurements to non-local sea state forcings such as the Wave Watch III model estimated wave heights driven by European Centre for Medium-Range Weather Forecasts (ECMWF) forecast winds, with a resulting significant improvement in retrieval uncertainty, especially at higher wind speeds (Pascual et al., 2021). The root-mean-square difference between the updated CYGNSS wind speeds and co-located ECMWF Reanalysis Version 5 (ERA5) winds for a one-year population of matchups is less than 2 m/s for wind speeds below ~10 m/s and increases to ~3 m/s at 20 m/s due to a gradual decrease in the sensitivity of the ocean surface scattering cross-section to changes in wind speed at the higher wind speeds. The possible influence of ECMWF winds were compared with results using ASCAT, WindSat, and AltiKa and showed no significant influence.

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 new version (v2.0) of the CYGNSS Ocean Surface Heat Flux product was released in 2022 that provides the time-tagged and geolocated ocean surface heat flux parameters with 25x25 km footprint resolution. Version 2.0 uses CYGNSS v3.1 surface wind speeds and ERA5 thermodynamic variables. The CYGNSS LHF and SHF products have been used in recent Madden–Julian Oscillation (MJO) convection and extratropical cyclone (ETC) analyses. CYGNSS is able to observe the equatorward side of the ETC systems, which contain the strongest winds and air-sea temperature differences, leading to strong LHF and SHF values. These observations provide insight into the impact of the heat fluxes on ETC genesis and evolution (Naud et al., 2021).

Major Refinement to the Version 07 IMERG Code: Close collaboration between a group using IMERG and the IMERG development team resulted in major refinements to the then-draft Version 07 IMERG code. Rajagopal et al. (2021) demonstrated that peak precipitation rates for storm systems were systematically higher when a passive microwave (PMW) overpass occurred, then diminished when time-interpolated data had to be used due to the averaging necessarily applied in the Kalman filter interpolator. In response, Tan et al. (2021) developed the Scheme for Histogram Adjustment with Ranked Precipitation Estimates in the Neighborhood (SHARPEN), which applies a kind of quantile mapping in the local region to approximately calibrate the interpolated data to the distribution of precipitation rates found in the input to the averaging process. In particular, the time series of extreme values in a storm system vary realistically with time. SHARPEN is now implemented in Version 07 IMERG.

New Satellite-Gauge Precipitation Dataset: One limitation in precipitation analysis is the sluggish pace at which surface gauge data are made available for use. Funk et al. (2022) describe a new satellite-gauge precipitation dataset, the Climate Hazards Center (CHC) IMERG with Stations (CHIMES), that augments IMERG-Late with a high-resolution climatology (a blend of gauge and satellite data) and the available supply of global gauge data that are reported relatively quickly. A preliminary analysis uses sparse near-real-time reports, while a final analysis has additional, carefully curated gauge data. One key step is that the gauge and satellite data are combined at 5-day and monthly intervals, which greatly increases the representativeness of the gauge data and skill of the combined product. These enhancements raise the explained variance between the satellite-based products and pentadal, high-quality gridded station data from 50% to 75% for the CHIMES product, while reducing the mean absolute error from 48 to 27 mm/mo.

Improving Characterization of the Hadley Circulation: The intertropical convergence zone (ITCZ) is where convective storm systems in the tropics account for much of the vertical movement of air, contributing to the global overturning circulation known as the Hadley circulation. In the Eastern Pacific region, there is disagreement in the characteristics of this overturning circulation among different data sets. Huaman et al. (2022) use observations from the Organization of Tropical East Pacific Convection (OTREC) 2019 field campaign, reanalysis data, and Global Precipitation Measurement (GPM) DPR latent heating estimates to compare representations of this circulation. This circulation is found in observations to have a shallow and a deep mode. In model analyses, the shallow mode dominates while GPM data shows the dominance of the deep mode. The satellites estimates were improved when information from CloudSat was included to represent a low cloud mode that cannot be readily detected by the sensitivity limitations of DPR.

Characterizing the Inner Core Rainfall of Tropical Cyclones: Guzman and Jiang (2021b) use 19 years of Tropical Rainfall Measuring Mission (TRMM) and GPM data to characterize the inner core rainfall of tropical cyclones around the globe. Based on a sample of 1789 tropical cyclones over the period, they found that Atlantic storms were characterized by significantly heavier rainfall than storms in other ocean basins. They attributed the greater rainfall to a number of environmental characteristics, including higher convective available potential energy, a drier mid-level environment, colder temperatures in the upper troposphere, and stronger vertical wind shear compared to other basins. Additional understanding of these factors is needed.

Climatology and Retrievals of Mean Precipitation Particle Sizes: One of the key advances of the GPM radar over the TRMM radar is its use of two radar frequencies that allows for improved estimation of mean precipitation particle sizes, a key indicator of cloud microphysical properties in precipitation systems. Han and Braun (2021) use 6 years of DPR observations to examine the climatology of mean particle size global and as a function of altitude. Variability of particle size is intimately tied to the distribution of convective and stratiform precipitation type and the depth of convection. Significant differences are also found between particle sizes over land versus ocean. Duffy et al. (2021) address whether the accuracy of retrievals of mean particle size from dual-wavelength ratio measurements are superior to estimates derived directly from the reflectivity measurements. They use airborne remote sensing and in-situ observations from multiple GPM field campaigns to demonstrate that dual-wavelength ratio estimates remain consistent across a range of storms and environments while estimates from reflectivity profiles show considerably greater variation. They confirm that the dual-wavelength ratio estimates provide more accurate estimates of particle size.

Characterizing the Diurnal Cycle of Rainfall: A key focus of the TRMM and GPM missions was the characterization of the diurnal cycle of rainfall, with an implicit assumption that the radar and passive microwave sensors would exhibit similar diurnal signals. Hayden and Liu (2021) combined 16 years of TRMM and 4 years of GPM data and compared measured diurnal cycles from the radars, radiometers, and the IMERG multi-satellite analysis, validated against ground observations over the southeastern United States. They found that the spaceborne radars provided the best representation of the magnitude and phase of the diurnal cycle while time delays were found in the passive microwave and IMERG estimates. IMERG was found to overestimate global precipitation and have time lags that tend to be larger and earlier over regions with organized convective systems.

Assessing Terrestrial Gamma Ray Flashes (TGFs) produced by Convective Storms: Tiberia et al. (2021) examined the three-dimensional structure of nine convective storms producing TGFs using data from GPM DPR and GPM Microwave Imager (GMI). Not surprisingly, the storms generating TGFs were characterized by deeper development with thick layers of high ice water content and high radar reflectivities (>50 dBZ), consistent with strong vertical air motions. Due to the strong scattering of radiation by ice, these storms were characterized by very strong depressions in microwave brightness temperatures, with 7 of 9 cases likely characterized by the presence of hail or graupel.

Detection and Measurement of Precipitation for Extreme Lake-effect Snowfall Events: Milani et al. (2021) studied the ability of GPM to detect and measure precipitation for extreme lake-effect snowfall events over the U.S. Great Lakes region. While the GMI was able to detect the shallow convective snowfall bands or cells, the precipitation retrieval algorithm inconsistently retrieved the amount of snowfall from these events and produces abundant light snowfall rates that do not match observations. Errors in the retrieval algorithm are related back to an a priori database that underrepresents the conditions represented in these events.

Global 3 Hourly Maps of Precipitation on a ~10 km Resolution Grid: Kemp et al. (2022) describe a new NASA–Air Force Precipitation Analysis (NAFPA) that combines precipitation estimates from numerical models, rain gauges, and satellites to produce global 3 hourly maps of precipitation on a grid with about 10 km resolution. While the Air Force system employs several legacy satellite products, they are shifting to IMERG Early Run as the primary source due to perceived limitations in the legacy products. Test runs for multiple years were evaluated over the continental U.S. (CONUS), Africa, and monsoonal Asia against best-available gauge analyses and compared to a range of other observational and numerical model global precipitation products, including the IMERG Late and Final Run products. For most metrics in these regions NAFPA performed better than most of the near-real-time products and was competitive with the post-real-time products. Operational implementation is underway to provide precipitation input to an operational Air Force land data assimilation system, and to provide improved precipitation information for Air Force interests.

Satellite-based Characterization of Convection and Impacts from the Catastrophic August 10, 2020 Midwest U.S. Derecho: Bell et al (2022) highlight a diverse array of remote sensing observations that were used to analyze the catastrophic August 10, 2020 derecho over the Midwest United States. Low earth orbit (LEO) passive-microwave imagers and 1-min-resolution GOES-16 products were used to track and characterize the evolution of the storm system. The coldest GOES-16 IR temperature, greatest flash extent density (FED), and highest GridRad echo tops and hail differential reflectivity (HDR) (indicative of intense updrafts likely to have generated hail) were highly correlated across the parts of Iowa where the highest winds, power loss, and discernable hail damage in agricultural crops occurred. Several areas of decorrelation were noted where high winds were driven primarily by a cold pool from complex 4D dynamics and precipitation within the derecho storm system. These analyses demonstrate how GOES-16 and GridRad can be applied to study severe storm evolution and highlight opportunities for using satellite IR and lightning observations within cloud tops to infer severe weather conditions at the ground. A pair of passive-microwave radiometer observations from Special Sensor Microwave Imager Sounder (SSMIS) and Advanced Microwave Scanning Radiometer 2 (AMSR2) data can be used to infer regions with the most intense convection and scattering by large and/or high concentrations of ice particles. The spatial resolution of the passive-microwave sensors has a strong impact on the ability to resolve these smaller-scale convective phenomena. Data and imagery captured by additional LEO satellites and photographs were used to assess the derecho's impacts to the land surface. Optical remote sensing instruments observed power outages, grain storage bins transported over large distances by extreme winds, and scarring of the land surface believed to be caused by wind-driven hail. Using European Space Agency (ESA) Sentinel-1 data, researchers demonstrated a statistical approach to identify specific damaged pixels in the corn and soybean crops in post-derecho acquisitions. This approach was validated using aerial imagery captured in the days after the derecho. The damage estimates of the corn and soybeans generated from this technique were then compared to estimates from other sources, showing very good agreement.

Development of an Algorithm to Retrieve Wind Speed Across the DPR-Ku Radar Swath: In a new use for GPM DPR data, Panfilova and Karaev (2021) developed an algorithm to retrieve wind speed across the DPR-Ku radar swath based on the normalized radar cross section (NRCS). Nadir-equivalent NRCS values were estimated across the swath using the geometrical optics approximation for the off-nadir footprints. These equivalent NRCS nadir values were regressed against wind speed data from ocean buoys. Validation against Advanced Scatterometer (ASCAT) data showed nearly unbiased results except with positive bias at speeds below about 3 m/s. DPR can see closer to shore than ASCAT due to smaller footprints but cannot provide estimates when the rain rate exceeds 0.5 mm/hr, while ASCAT is all-weather. Thus, the two sensors are somewhat complementary and the DPR algorithm is being pursued.

Identifying Constellation Attributes Needed for Continued Global Precipitation Observation: GPM's pioneering work in using the international constellation of satellites carrying passive microwave instruments for the past two decades gives important insights into the constellation attributes needed for continued global precipitation observation. Key issues that Kidd et al. (2021) identify are: sufficiently fine spatial resolution (to resolve precipitation-scale systems and reduce beam-filling effects), channel diversity (to accommodate the range of precipitation types and intensities observed around the world), observation intervals commensurate with precipitation variability, and passive/active microwave sensors in non-Sun synchronous orbit (to provide an on-going, consistent source of calibration data).

Assessing Corrections for SSMIS Sensors to Improve Confidence in Brightness Temperature Data: The international constellation of satellites carrying passive microwave instruments is an integral part of GPM. As such, GPM carries out world-class adjustments and calibrations that permit confident use of the brightness temperature data in GPM algorithms and that are freely distributed to the science community. Kroodsma et al. (2022) reexamined the corrections that were developed for the SSMIS sensors aboard the Defense Meteorological Satellite Program (DMSP) F16-F19 satellites over a decade ago, addressing a list of known and suspected issues that have been reported since then. Upgrades include geolocation and viewing geometry, along-scan bias adjustments, sun angle correction using data from each entire mission, enhanced corrections for the high-frequency channels, and improved channel-to-channel corrections. Collectively, these provide an important improvement in quality and consistent performance for the new GPM V07 datasets.

CYGNSS and Geostationary Environmental Monitoring and Characterization

Freeze/Thaw Detection: Changes in CYGNSS reflectivity are able to detect transitions in the Freeze/Thaw state of land surfaces (Carreno and Ruf, 2021). 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. The CYGNSS observations have superior spatiotemporal sampling as compared to previous methods. The method used in this study was based on a seasonal threshold algorithm and validated using surface temperature data from the ERA5 land temperature numerical model.

Hydrologic Model Parameter Estimation in Ungauged Basins Using Simulated Surface Water and Ocean Topography (SWOT) Discharge Observations: In-situ gauge networks are often used in hydrologic model calibration, but these networks are limited or nonexistent in many regions. The upcoming SWOT mission promises to fill this observation gap by providing discharge estimates for rivers wider than 100 m. SWOT observation utility for model parameter selection in regions devoid of in-situ gauges is assessed using proxy SWOT discharge estimates derived from an observing system simulation experiment and Monte Carlo methods. The sensitivity of the parameter selection to measurement error and observation frequency is also evaluated. Single- and multi-point parameter selection are performed for ten subbasins within the Susitna and upper Tanana river basins in Alaska. SWOT is expected to observe Alaskan river points 4–7 times per 21-day repeat cycle with 120-km swath coverage. For an expected SWOT measurement error of 35%, parameter estimation is successful for 50% (90%) of sub-basins using single- (multi-) point parameter selection. Decreasing observation frequency to simulate lower latitudes resulted in success for only 10% of midlatitude and tropical sub-basins for single-point selection, whereas multipoint selection was successful in 80% (60%) of midlatitude (tropical) sub-basins. Single-point parameter selection is more sensitive to measurement error than multi-point parameter selection. The results strongly support the use of multi-point over single-point parameter selection, yielding robust results nearly independent of observation frequency. Most importantly, this study suggests SWOT can be used to successfully select hydrologic model parameters in basins without an in-situ gauge network.

Relating Lightning Flash Rates to Precipitation Features: Heuscher et al (2022) use GPM derived precipitation features (PFs) in combination with data from the Geostationary Lightning Mapper (GLM) on NOAA GOES to relate lightning flash rates with the characteristics of the PFs. The cold microwave brightness temperatures of the lightning-producing PFs are well correlated with ice mass concentrations in deep convective precipitation systems, with high lightning-flash-rates storms generally being less sensitive to environmental conditions than low flash rate storms.

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 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 has collected data from over 15 winter storms that occurred in winters 2020 and 2022. Several publications (Dunnavan et al., 2022; Finlon et al., 2022; Miller et al., 2022) have resulted from the analysis of the 2020 data. An overview article (McMurdie et al., 2022) appeared in the flagship journal of the American Meteorological Society that describes the IMPACTS project and highlights preliminary results from the 2020 deployment. One study investigated the microphysical properties within regions of enhanced dual-frequency ratio (DFR). Understanding how DFR changes with microphysical properties informs how algorithms can be improved to measure precipitation from space borne instruments. That study found that regions of prominently higher Ku- and Ka-band DFR were characterized by larger mass-weighted mean diameter, smaller effective density and fewer particles than in regions of lower DFR. These microphysical characteristics are consistent with significant aggregation and are related to increased snowfall rates on the ground. Other studies utilized IMPACTS data to study snow growth processes in the layer of the atmosphere where dendritic shaped ice crystals are prominent. Another described the survival of snow in the melting layer and the effect of relative humidity on snowflake survival. Together these studies are advancing our understanding of snowfall distribution within winter storms. In 2023, the project will have the last opportunity to sample winter storms, and the team plans to continue their studies of precipitation processes, remote sensing, and modeling of snowfall within precipitating storms.

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

Convective Processes Experiment – Aerosols and Winds (CPEX-AW): CPEX-AW was a joint NASA-ESA field campaign primarily focused on validation of ESA's Atmospheric Dynamics Mission-Aeolus (ADM-Aeolus) spaceborne wind lidar based out of St. Croix, U.S. Virgin Islands (USVI) using the NASA DC-8 during late August through early September 2021. ADM-Aeolus is the world's first spaceborne wind lidar, providingvertical profiles of line of sight horizontal winds. CPEX-AW were designed to perform a number of ADM-Aeolus underflights to validate the satellite observation. In addition to validation of ADM-Aeolus, CPEX-AW leveraged its cutting-edge suite of active (e.g., High Altitude Lidar Observatory [HALO], Doppler Aerosol WiNd Lidar [DAWN], Airborne Third Generation Precipitation Radar [APR-3]) and passive (e.g., High Altitude Monolithic Microwave integrated Circuit [MMIC] Sounding Radiometer [HAMSR], dropsondes) dynamic, thermodynamic, and composition profilers to sample Saharan dust interactions with the convective environment of the Caribbean, convection in the ITCZ, and several tropical systems, including Tropical Depression Kate, Hurricane Larry, and most notably Hurricane Ida during its transition from a tropical wave to a tropical storm. Publication quality data from CPEX-AW is available through Global Hydrometeorology Resource Center (GHRC) and Atmospheric Science Data Center (ASDC) Distributed Active Archive Centers (DAACs). The field portion of the CPEX-AW mission ended prematurely due to programmatic considerations. The Convective Processes Experiment – Cabo Verde (CPEX-CV) is a continuation of CPEX-AW that will take place out of Cabo Verde during September 2022. CPEX-CV leverages the same DC-8 payload from CPEX-AW with the addition of in-situ sampling wing probes (Cloud, Aerosol, and Precipitation Spectrometer [CAPS]) to better characterize and link the optical and microphysical properties of the Saharan Air Layer dust particles back to observables from the active sounders on the NASA DC-8 and spaceborne instruments. The focus of CPEX-CV will be aimed towards investigating interactions between atmospheric dynamics, marine boundary layer processes, convection, and the dust-laden SAL as they emerge from the African continent. With the shift to Cabo Verde in 2022, CPEX-CV will provide critical observations in the data-sparse tropical eastern Atlantic region that will improve our predictive capability and understanding of process-level life cycles that impact downstream convective and tropical storm development, as well as Saharan dust transport.

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 FY2022 to (a) improve our ability to retrieve aerosol and clouds and diagnose their properties and elucidate their interactions and impacts upon radiation; (b) more fully characterize spatial and temporal variability of pollution on regional scales; better understand the impacts of wildfires in particular; and through both to improvements in weather and air quality forecasts; (c) better describe the carbon cycle budget and improve our capability to model it; and (d) use both satellite observations and large-scale models to understand the chemical and physical processes that control the pace of ozone recovery, now and in the decades to come as well as the evolution and impacts of aerosols injected into the upper atmosphere.

A. Aerosols, clouds & radiative forcing

Yu et al. (2021) use a comprehensive set of satellite and ground-based observations (including MODIS, CALIOP, SEVIRI, AERONET, and EPA Air Quality network), along with the NASA GEOS global aerosol transport model, to characterize a massive African dust intrusion into the Caribbean Basin and southern US in June 2020. Although the GEOS model compared well to MODIS observations that tracked the meandering dust plume, the model substantially underestimated the initial dust emission and did not lift up enough dust for the ensuing long-range transport. Consequently, the model largely missed the satellite-observed elevated dust plume, underestimating the dust intensity in the Caribbean by a factor of 4.

The atmospheric abundance of dust is unconstrained in cirrus-forming regions, hampering our ability to predict these radiatively important clouds. **Froyd et al. (**2022) present global-scale measurements of dust aerosol abundance in the upper troposphere and incorporate these into a detailed cirrus-formation model. They show that dust aerosol initiates cirrus clouds throughout the extra-tropics in all seasons and dominates cirrus formation in the Northern Hemisphere (75–93% of clouds seasonally). Their findings establish the critical role of dust in Earth’s climate system through the formation of cirrus clouds.

Nastan (2022) focuses on the applicability of MAIA data to the management of visibility impairment from regional haze in the United States and connections to the US EPA Regional Haze Rule, describing how the speciated particulate matter products that will be generated by MAIA could augment mandated evaluations of trends in visibility and PM composition, particularly for the state-level studies that are expected to be due in 2028.

Van Donkelaar et al. (2021) developed a methodology for monthly estimates and uncertainties of PM2.5 that combines satellite retrievals of aerosol optical depth, chemical transport modeling, and ground-based measurements to allow for the characterization of seasonal and episodic exposure. They find that South Asia and East Asia continue to be two of the top contributors to the global PM2.5 levels, with regional population-weighted monthly mean PM2.5 concentrations often exceeding 90 $\mu g/m^3$. These findings will aid the air-quality management on both global and regional scale.

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

Ozone and regional air quality

The 2017 Lake Michigan Ozone Study (LMOS 2017) was a collaborative, multi-agency field study targeting ozone chemistry, meteorology, and air quality in the southern Lake Michigan area (**Stanier et al, 2021**). The data collected during LMOS 2017 are being used to help air quality management agencies prepare for using data from the Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument as soon as they become available next year. **Wagner et al** (2022) present detailed characterization of the lake breeze behavior during LMOS 2017, quantifying the well-known sharp changes in wind direction, temperature, water vapor, and stability at time of lake breeze arrival. Kinematic and thermodynamic profilers locations adjacent to the western shore of Lake Michigan enabled the analysis of lake-breeze structure in unprecedented detail, and a compelling portrait of the development of this phenomenon has emerged from the synthesis of these instruments and surface measurements.

Torres-Vazquez et al. (2022) use NASA-supported measurements from the Long Island Sound Tropospheric Ozone Study (LISTOS) to evaluate state-of-the-art chemical WRF-CMAQ transport modeling done by the US EPA. They find better simulations of air quality exceedance events relative to the baseline as shown by the air quality monitoring network and enhanced measurements during LISTOS including ozonesondes, the Langley Mobile Ozone Lidar (LMOL), and the GEO-CAPE Airborne Simulator. Results based on this modeling framework provide confidence for states to make regulatory decisions for achieving air quality standards.

Wildfires and ozone chemistry

Wolfe et al. (2022) elucidate key connections within gas-phase photochemistry in large wildfires and assess novel chemical processes via a case study of the 2013 California Rim Fire plume. Inclusion of estimated unmeasured volatile organic compounds (VOCs) leads to a 250 % increase in OH reactivity and a 70 % increase in radical production via oxygenated VOC photolysis. The addition of HONO (representing primary emissions) or particulate nitrate photolysis amplifies ozone production, while heterogeneous conversion of NO_2 suppresses ozone formation. Analysis of radical initiation rates suggests that oxygenated VOC photolysis is a major radical source, exceeding HONO photolysis when averaged over the first 2 h of aging. Ozone production chemistry transitions from VOC-sensitive to NO_x-sensitive within the first hour of plume aging, with both peroxide and organic nitrate formation contributing significantly to radical termination. To simulate smoke plume chemistry accurately, models should simultaneously account for the full reactive VOC pool and all relevant oxidant sources.

Xu et al. (2021) investigate the highly variable O_3 chemistry in wildfire plumes, a substantial but poorly quantified source of tropospheric ozone. They exploit the *in situ* chemical characterization of western wildfires during the FIREX-AQ flight campaign to show that O_3 production can be predicted as a function of experimentally constrained OH exposure, VOC reactivity, and the fate of peroxy radicals. The O_3 chemistry exhibits rapid transition in chemical regimes. Within a few daylight hours, the O_3 formation substantially slows and is largely limited by the abundance of nitrogen oxides (NO_x). This finding supports previous observations that O_3 formation is enhanced when VOC-rich wildfire smoke mixes into NO_x-rich urban plumes, thereby deteriorating urban air quality.

C. GHG sources, sinks, fluxes and trends

Emissions of hydrofluorocarbons (HFCs) have increased significantly in the past 2 decades, primarily as a result of the phaseout of ozone-depleting substances under the Montreal Protocol and the use of HFCs as their replacements. **Velders et al.** (2022) analyze trends in HFC emissions inferred from observations of atmospheric abundances and compare them with previous projections. Total CO_2 equivalent-inferred HFC emissions continued to increase through 2019 but were about 20 % lower than previously projected for 2017–2019, mainly because of the lower global emissions of HFC-143a. This indicates that HFCs are used much less in industrial and commercial refrigeration (ICR) applications than previously projected.

D. Stratospheric composition change and ozone depletion

Aviation impacts

Supersonic aircraft will have environmental impacts distinct from those of subsonic aviation and are once again being developed and bought. **Eastham et al.** (2022) assess the impacts on atmospheric composition and non-CO_2 climate forcing of a near-future supersonic aircraft fleet with current-generation engine technology burning fossil-based kerosene fuel with current-day sulfur content. They estimate a net non-CO_2, non-contrail forcing of -3.5 mW m^{-2}, varying from -3.0 to -3.9 mW per m^2 per year to year. They also show that the use of zero-sulfur fuel would halve net ozone depletion but increases the net non-CO_2 non-contrail forcing to +2.8 mW m^{-2} due to the loss of a cooling effect from sulfate aerosols. Their results show that assessments of near-future supersonic aviation must consider the effects of fuel sulfur and black carbon alongside emissions of water vapor, NO_x, and CO_2 and that the net environmental impacts will be a trade-off between competing environmental concerns.

Ozone recovery and trends

Without the Montreal Protocol, the already extreme Arctic ozone losses in the boreal spring of 2020 would be expected to have produced an Antarctic-like ozone hole, based upon simulations reported by **Wilka et al**. (2021). Using a specified dynamics version of the Whole Atmosphere Community Climate Model (SD-WACCM) and an alternate emission scenario of 3.5 % growth in ozone-depleting substances from 1985 onwards, they find that the area of total ozone below 220 DU (Dobson units) would have covered about 20 million km^2. Without the Montreal Protocol, springtime ozone depletion would have begun earlier and lasted longer, and by 2020, the year-round ozone depletion would have begun to dramatically diverge from the observed case. This study reinforces that the historically extreme 2020 Arctic ozone depletion is not cause for concern over the Montreal Protocol's effectiveness but rather demonstrates that the Montreal Protocol indeed merits celebration for avoiding an Arctic ozone hole.

Impacts of wildfires on the stratosphere

Strahan et al. (2022) used OMPS LP, MLS, and ground-based measurements to investigate perturbations in stratospheric composition after the January 2020 Australian wildfires that injected record-breaking amounts of smoke into the southern stratosphere. They find that midlatitude chlorine (Cl_y) was significantly repartitioned from March to September 2020 (3-7 months after the peak of Australian fires) likely via heterogeneous chemical reactions on the wildfire aerosols with the greatest effect at polar latitudes where polar nights are the longest. Model simulations using stratospheric sulfate aerosol reactions were unable to reproduce the observed changes in the chlorine species revealing the need for understanding chemical reactions that occur on wildfire aerosols to predict impacts on stratospheric ozone if massive wildfires occur more often in a warming climate.

Section 1.1.9.2 Carbon Cycle and Ecosystems Focus Area

Contributions from the Carbon Cycle and Ecosystems Focus area to Annual Performance Indicator 1.1.9 included better constraining greenhouse gas and methane sources and sinks to reduce uncertainties, further understanding the natural and human-induced changes on global biodiversity, and characterizing processes that control aquatic ecosystems and their future changes.

Ocean Biology and Biogeochemistry

Marine ecosystems are responding to anthropogenic forcings, and complex ecosystem models are being developed to better predict changes in phytoplankton community composition and ocean ecology. Under high-emission scenarios, climate change will lead to a major biomass decline in future oceans for the tropics and temperate regions, with biomass increasing at high latitudes (Henson et al., 2021). This shift will lead to substantial changes in phytoplankton diversity and community composition, which has the potential to negatively impact the entire marine food web. With decreases in diversity, phytoplankton community resilience is also predicted to decrease, creating more unstable marine ecosystems (Anderson et al., 2021).

To predict and better understand the impacts of climate change on the ocean ecosystem under future climate scenarios, mechanistic ocean models are employed to reveal how the community structure currently functions and will evolve. In ecosystem models, phytoplankton population controls are often based only on physical variables, like temperature or ocean currents. Clark and Mannino (2022) recently revealed the impacts of physical variables like wind velocity and freshwater input from high latitude rivers as driving factors on nutrient input into the coastal and ocean ecosystem by leveraging a three-dimensional hydrodynamic model to study the Yukon River outflow into the Bering Sea. Since physical forcing and nutrient availability are important predictors of ocean ecology, Carroll et al. (2022) leveraged the ECCO-Darwin model to create a state estimate of the time and space distribution and variability of dissolved inorganic carbon, as influenced by ocean circulation, biology, and carbon dioxide fluxes into and out of the ocean. They were able to quantify key divers and processes within the global ocean affecting the fate and sequestration pathways of carbon to better our understand and predict the climate sensitivity of marine ecosystems. However, physical variables alone can be insufficient to explain species' distribution in ecosystem models. For example, Prochlorococcus, the smallest and most abundant photosynthetic organism on Earth, was thought to be confined to low-latitude regions only by its requirement for warm waters. However, its poleward decrease is caused by ecological interactions and the presence of a shared predator, previously unknown. Follett et al (2021), using direct observations from data collected during poleward research cruises, revealed this new population dynamic, which in turn was used to improve the ecosystem model's function, highlighting the need to pair observations with marine ecosystem models to better understand ecosystem function and enable more accurate predictions. Future NASA hyperspectral satellite sensors, such as PACE, SBG, and GLIMR, will similarly be able to provide observations of phytoplankton community composition and dynamics, which can be incorporated into models to develop a more robust predictive understanding and to reveal critical changes in community structure and ecosystem resilience across the global ocean under a changing climate.

Terrestrial Ecology

Greenhouse Gas dynamics across terrestrial ecosystems

Understanding greenhouse gas (GHG) dynamics across ecosystems, and the drivers that control the release and sequestration of GHG, is a priority as ecosystems currently play a key role in mitigating climate change. Wildfires in boreal forests release large quantities of GHG to the atmosphere, exacerbating climate change. Phillips et al. (2022) characterized the magnitude of recent and projected gross and net boreal North American wildfire carbon dioxide emissions, evaluated fire management as an emissions reduction strategy, and quantified the associated costs. Their results showed that wildfires in boreal North America could, by mid-century, contribute to a cumulative net source of nearly 12 Pg of carbon dioxide, about 3% of remaining global carbon dioxide emissions associated with keeping temperatures within the Paris Agreement's 1.5°C limit. With observations from Alaska, Phillips et al. (2002) showed that current fire management practices limit the burned area. Further, the costs of avoiding carbon dioxide emissions by means of increasing investment in fire management are comparable to or lower than those of other mitigation strategies. Together, these findings highlight the climate risk that boreal wildfires pose and point to fire management as a cost-effective way to limit emissions.

Arctic Boreal Vulnerability Experiment (ABoVE) scientists continue to make progress in understanding the occurrence and controls of methane (CH_4) hotspots, areas of intense CH_4 emission, from northern ecosystems using AVIRIS airborne imaging spectroscopy and ground-based observations. Baskaran et al. (2022) studied geomorphological controls on methane hotspots in the Mackenzie Delta region in northern Canada. They found differences in hotspot distribution between uplands and lowlands attributed to topography and geomorphology controls. They also found distinct differences in hotspot pattern behavior based on ecoregions, and most of the patterns could be explained by the proximity to water and the height of the water table. These observations provide important clues about the underlying mechanisms of methane hotspot formation and facilitate statistical extrapolations of the relationship to larger regions. Further constraining CH_4 hotspot emissions across the pan-Arctic is important, given the disproportionate contribution of methane to climate change; to this end, Elder et al (2021) quantified thermokarst CH_4 emissions on different spatial scales and were able to extrapolate their results to the terrestrial pan-Arctic. The authors estimated that thermokarst CH_4 hotspots constitute less than 0.01% of the pan-Arctic land area but contribute roughly 4% of annual pan-Arctic wetland emissions. Elder et al (2021) also identified a previously undiscovered CH_4 hotspot at Big Trail Lake (AK), with hotspot emissions confined to <1% of the lake. Ground-based chamber measurements revealed thawed permafrost directly beneath it and extending to a depth of ~15 m, indicating that the intense CH_4 emissions likely originated from recently thawed permafrost. Hotspot emissions accounted for ~40% of total diffusive CH_4 emissions from the lake study site. These results suggest that significant proportions of pan-Arctic CH_4 emissions originate from disproportionately small areas of previously undetermined thermokarst emissions hotspots, and that pan-Arctic CH_4 emissions may increase non-linearly as thermokarst processes increase under a warming climate.

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. Hurtt et al (2022) recently published a synthesis of NAS CMS 'Phase 2' activities (2011–2019), which encompasses 79 projects, 482 publications, and 136 data products. The review describes CMS activities to date and discuss current research gaps as well as future priorities in carbon monitoring research and applications. For example, a CMS-identified gap to developing gridded carbon products is accurate quantification and application of the allometric equations needed to create and scale-up reliable biomass reference data. An identified CMS priority is to enable the next generation of satellite observations of methane.

Land Cover/Land Use Change

Urban greenspace

A fundamental challenge in verifying urban CO_2 emissions reductions is estimating the biological influence that can confound emission source attribution across heterogeneous and diverse landscape; this impedes flux quantification and decision making. To address this problem, Parazoo et al. (2022) utilized new high-resolution maps of land cover (0.6 m) and irrigation (30 m) derived from optical and thermal sensors to simultaneously resolve landscape influences related to vegetation type (tree, grass, shrub), land use, and fragmentation needed to accurately quantify biological influences on CO_2 exchange in complex urban environments. The team integrated these maps with the Urban Vegetation Photosynthesis and Respiration Model (UrbanVPRM) to quantify spatial and seasonal variability in gross primary production (GPP) across urban and non-urban regions of Southern California Air Basin (SoCAB). Results showed that land use and landscape fragmentation have a significant influence on urban GPP and canopy temperature within the water-limited Mediterranean SoCAB climate. Cooling from irrigation alleviated strong warming along greenspace edges within 100 m of impervious surfaces, and increased GPP by a factor of two, compared to non-irrigated edges. They also noted that non-irrigated shrubs were typically more productive than non-irrigated trees and grass, and equally productive as irrigated vegetation. These results imply a potential water savings benefit of urban shrubs, though more work is needed to understand carbon vs water usage tradeoffs of managed vs. unmanaged vegetation.

Biodiversity

The ability to track the impacts of natural and human-induced changes on global biodiversity has resulted in improved decision-making and conservation action. This information is critical to predict trends and derive projections of natural ecosystems health and the services they provide humans. While many countries and global organizations have conservation policies, knowledge gaps that make these policies less effective can still occur. Oliver et al (2021) analyzed national trajectories for the location and spacing of terrestrial vertebrates. They found that a nation's biodiversity data coverage and sampling effectiveness was most complete for the most populous species in a nation - with rarer and more threatened species often lacking adequate data records. In addition, developing nations generally lacked biodiversity data records of other countries. Despite increasing data availability for all taxa, most nations are not making progress in closing information gaps for mammals, amphibians, and reptiles. Satellite biodiversity observations can provide a means of filling these critical data gaps and developing a global language of biodiversity conservation. For instance, Jetz et al (2022) demonstrated how a derived Species Protection Index (SPI), relating satellite-informed species distribution maps to national protected area distribution, would support national and global assessment of conservation needs. This measurement provides a framework to achieve the Convention on Biological Diversity's goal of having "healthy and resilient populations of all species" and "reduced extinction rates."

Section 1.1.9.3 Climate Variability and Change Focus Area

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

Scientists have discovered that glaciers in Southeast Greenland are harboring a previously unknown subpopulation of polar bears. The bears, which are uniquely adapted to their environment, could provide insight on the future of the species in a warming Arctic. *Laidre et al. (2022)* combined 36 years of movement, genetic, and demographic data to show that polar bears in Southeast Greenland are distinct from bears living elsewhere along the island's eastern coast. Instead of traveling large distances to hunt on sea ice, polar bears in Southeast Greenland are relatively stationary; they live and hunt solely in the region's glacial fjords at the interface of glacier ice and sea ice/mélange. The unique population has been isolated from similar polar bears in the Arctic for long enough that they have become genetically distinct. The team used Moderate Resolution Imaging Spectroradiometer (MODIS) data, as well as in situ data to document the conditions in the fjords and the offshore sea ice environment. They found that southeastern polar bears are cut off from sea ice for two-thirds of the year, and instead rely on mélange in these glacial fjords to hunt. Based on these observations and conclusions, the team surmises that the manner in which southeastern polar bears have adapted could be an indication of how other polar bear populations may adapt to survive as global warming persists. The study was funded in part by NASA's Biological Diversity and Cryospheric Sciences programs.

Sea Ice in the Climate System

The indicators of rapid climate change in the Arctic (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. This uncertainty limits the ability to predict the magnitude of future wintertime warming. In order to better constraint these fluxes within the Coupled Model Intercomparison Project 6 (CMIP6), *Boisvert et al. (2022)* used the observation-derived turbulent flux dataset product using NASA's Atmospheric Infrared Sounder (AIRS) collected during Arctic winter to better predict the magnitude of future wintertime warming. Their results show that CMIP6 models represent the surface turbulent fluxes in the central Arctic differently from observations, as a heat source rather than a heat sink to the winter Arctic atmosphere like observations. Both observations and models show that the turbulent fluxes have increased the most in areas of fast ice loss, whereas in areas of persistent ice cover there has been relatively little change; there is a distinctive relationship between modeled trends in future surface turbulent fluxes and decreasing sea ice coverage with anticipated persistent Arctic warming during the winter months.

Seasonal variability in Arctic sea ice (such as the onset of melt and the start of freeze-up) are notably useful metrics for assessing sea ice in climate models in comparison to observations. In order to determine melt onset from space, satellite sensors measure observed brightness temperature of the sea ice surface, however climate models do not incorporate this parameter and thus must define melt onset with other modeled variables instead. *Smith et al. (2022)* adapted a passive microwave sea ice satellite simulator (the Arctic Ocean Observation Operator, or ARC3O) to give simulated brightness temperatures that could be used to determine timing of the earliest melt in climate models, specifically within the ocean-ice hindcasts in the Community Earth System Model Ver. 2 (CESM2). The team used the model to develop a new metric for melt onset ("earliest snowmelt estimation"), which was designed to determine the beginning of snowmelt based on when it first occurred in the simulation. This new metric facilitated new comparisons between model and satellite observations (specifically AMSR and DMSP in this study) by removing uncertainty that comes about from differences between observed surface brightness temperatures and proxy values for this variable in models. By using a satellite simulator to produce metrics not inherent in climate models, they showed that it is possible to overcome limitations in model projections of seasonal sea ice variability using such simulations which should allow for more realistic model assessments of future sea ice conditions in the future.

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. *Felikson et al. (2022)* built a computer model that forces a "typical" glacier to retreat independent of seasonal changes of terminus movement. Their results show that omitting seasonality can cause a misrepresentation of mass loss estimates based on bed topography and the amount of seasonal terminus movement. They found that over- or under-estimates of mass loss are extremely sensitive to the amount of seasonal terminus movement, and not particular sensitive to basal friction laws; these results emphasize that models need to take seasonal changes into account in order to avoid erroneously quantifying predictions of glacier mass loss moving forward.

A combination of airborne and ground science data collection campaigns, as well as measurements taken by satellites, are critical tools for understanding remote parts of the cryosphere. Monitoring the surface mass balance of the Greenland ice sheet with in situ surface measurements provide necessary measurements that often cannot be observed by airborne or spaceborne sensors, and these direct observations are critical inputs for modeling ice sheet mass loss. *Howat (2022)* presented a 3-year record of weekly snow water equivalent (SWE) accumulation at Summit Camp on the central Greenland ice sheet obtained by direct sampling. Incorporating these in situ samples and long-term ice core estimates of SWE into surface mass balance reanalysis models showed that snow accumulation rates are significantly underestimated at Summit Camp, which may prove problematic in the future as these models are often used to estimate ice sheet mass loss.

Undercutting and subsequent submarine melting of grounded ice is a major physical process driving the retreat of Greenland glaciers. Most current ice sheet models do not include this critical process, and thus may significantly underestimate the mass loss from the Greenland Ice Sheet into the ocean. Humboldt Glacier is a 100-km wide, slow-moving glacier in north Greenland which holds enough ice to add roughly 19 centimeters to global sea level if melted away; as such, this glacier has been the fourth largest contributor to sea level rise since 1972 but the cause of its mass loss has not been explained. *Rignot et al. (2021)* used an ocean model to reconstruct grounded ice undercutting by the ocean and combine this with observed dynamic thinning from a variety of airborne (i.e., the Airborne Topographic Mapper) and satellite (ICESat, ICESat-2) altimetry, as well as observed grounding line retreat from the suite of available Landsat satellite imagery from the 1970s to present. Additionally, they present new bathymetry data in front of Humboldt Glacier that infer that the bed topography is 200 m deeper than previously reported at the ice front, hence more susceptible to melting from subsurface ocean waters and with a deeper bed channel to promote inland retreat of the grounding line. These new bathymetric observations confirm the presence of a deep channel underlying the northern sector of the glacier that may be conducive to fast retreat powered by the influx of relatively warm Atlantic Intermediate Water flowing further towards the head of the glacier. With the inference that AIW is causing melt further from the front of the glacier and the other directly observed and modeled components of glacier thinning and retreat, they concluded that more than 70% of the observed retreat is a direct result of ocean warming, while the remaining retreat can be attributed to dynamic thinning.

The basal thermal state (frozen or thawed) of the Greenland Ice Sheet is poorly understood due to few direct measurements, yet knowledge of these basal conditions are becoming increasingly important to interpret modern changes in ice flow. *MacGregor et al. (2022)* completed the first synthesis of basal thermal conditions, which required inferences from widespread airborne and satellite observations and numerical models, for which most of the underlying datasets have since been updated. In this updated version, the team combined constraints on the Greenland Ice Sheet's basal thermal state from boreholes, thermomechanical ice-flow models that participated in the Ice Sheet Model Intercomparison Project for CMIP6, IceBridge BedMachine Greenland v4 bed topography, the Greenland Ice Sheet Velocity Mosaic v1 (supported by the NASA MEaSUREs program) and multiple inferences of a thawed bed from airborne radar soundings. Their revised analysis of the Greenland likely Basal Thermal State version 2 (GBaTSv2) indicates that 33 % of the ice sheet's bed is likely thawed, 40 % is likely frozen and the remainder (28 %) is too uncertain to specify. This revised synthesis suggests that more of the northern Greenland ice sheet is likely thawed at its bed and conversely that more of the southern Greenland ice sheet is likely frozen, both of which influence the understanding of the ice sheet's present subglacial hydrology and models of its future evolution.

Despite the technologies available for ground-based data collection, satellites remain the only way in which we can collect sufficient data to improve projections and predictions of how the Earth's large bodies of ice will react to a changing climate. The future retreat rate for marine-based regions of the Antarctic Ice Sheet is one of the largest uncertainties in sea-level projections. It has been observed and heavily reported that the speedup of Pine Island Glacier in the Amundsen Sea Embayment region of West Antarctica has made it the ice sheet's largest contributor to sea level rise, and its continued rapid retreat may act to further destabilize the glacier. *Joughin et al. (2021)* used Copernicus Sentinel 1A/B- derived velocity measurements that show a speedup of greater than 12% over the past three 3 years, which is coincident with a 19-km retreat of the front of the ice shelf. Additionally, using an ice-flow model simulating ice loss, they found that accelerated calving can explain the recent glacier acceleration, outside of the melt-driven processes at the grounding zone that have been responsible for past periods of acceleration.

Another geographic area under intense monitoring for signs of increased contributions to sea level rise are the glaciers and ice shelves of the Antarctic Peninsula. *Wang et al. (2022)* studied the Larsen C Ice Shelf on the West Antarctic Peninsula using a variety of optical and synthetic aperture radar satellite datasets from a variety of NASA and ESA missions collected over 1963 to 2020 to derive a multidecadal time series of ice front position, flow velocities and rift features on the ice shelf in order to understand the processes that control its retreat. They found that the origin of rifts near ice rises, which interact with one another to cause additional mechanical strain in the ice shelf, were an important control on Larsen C front calving and flow acceleration over the past six decades, and that the total ice shelf area was reduced by more than 20% as a result of two large retreat cycles over the observational time series. They stressed that understanding how rift features create a feedback of changing stress conditions in the ice shelf is necessary for predicting future changes of ice shelf dynamics and incorporating these variables adequately into ice sheet system models. *Larour et al. (2021)* also investigated rifting processes of the Larsen C Ice Shelf, specifically the propagation of a major rift that led to the calving of one of the largest tabular icebergs on record, A68, in July 2017. Using modeling to simulate different conditions under which rift activation and propagation occur, they found that ice shelf thinning doesn't reactivate rifts, but on the contrary works to repair them. However, thinning of the mélange at the rift propagation site acts to control how quickly the rift continues to open, and reduction in this melange layer's thickness can often be sufficient enough to reactivate rifts and trigger large calving events like the one seen in July 2017. They determined that this interconnection between melange thinning and ice shelf rift propagation is likely showing a clear link between climate forcing and ice shelf retreat that has been omitted from ice sheet models in the past.

Oceans in the Climate System

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

Estimating the Circulation and Climate of the Oceans

With certain similarities with numerical weather forecasting, there are subtle but important considerations in ocean state estimation, namely conservation of basic physical properties such as heat, salt, or momentum, that require alternative data assimilation approaches. While budget closure is of little importance for weather forecasts, as their violation has no impact on short-range prediction skill, budget closure and thus absence of discontinuity in the analysis time when the model is forced toward the data, is crucial to the understanding of climate change and ocean's role in climate. NASA supports production of a robust estimate and evolution of ocean and sea ice state through development of the Estimating the Circulation and Climate of the Ocean (ECCO) framework (https://ecco-group.org). The framework integrates nearly all existing ocean satellite and in situ observations under the constraints of the conservation laws of physics, and provides 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 salt budgets, ocean-ice coupling, sea level rise, air-sea interaction, ocean water cycle, carbon cycle and biogeochemical changes. During this year, ECCO was utilized in 200 publications and numerous presentations, including the announcement of the *2021 Nobel Prize in Physics*.

One of the interesting applications of ECCO's budget machinery was the study by *Fukumori et al. (2021)*, who demonstrated how the melting sea ice drives sea level rise in the Arctic's Beaufort Sea, which exhibits one of the fastest rising sea level on Earth, nearing 15 mm/yr between 1993 and 2017. While sea ice melt causing level rise might seem at odds with conventional wisdom and Archimedes' principle, *Fukumori et al. (2021)* quantified the impact of melting sea ice on ocean freshening and consequent sea level rise through halosteric variations in ocean height. Specifically, as the winds in the Beaufort Sea become stronger over the past decades, the giant ocean current that swirls clockwise and referred to as Beaufort Gyre, traps more sea ice. Rapid melting of this trapped sea ice leads to anomalous freshening of the ocean surface. Fresher water is less dense, which means it takes a larger volume and thus sea level rise. Those salinity-induced variations in density and consequent expansion or contraction of the water column are referred to as the halosteric density and sea level changes. ECCO's sea ice mass budget closure and sea level attribution studies allowed one to tease out the impact of wind and sea ice on the fast rising seas in the Arctic's Beauforts Seas, with implications for prediction. The region's sea-ice meltwater content evolves slowly by the gyre's swirling circulation that keeps it in place. On the other hand, direct wind-driven change varies more rapidly as it only temporarily changes the direction of the flow. Therefore, in the absence of additional wind to drive the change, the melt water effect will likely last longer (years) than the ocean circulation change (weeks).

Another useful application of ECCO machinery this year was attribution of sea level rise along the US Northeastern coast, which is another hotspot of our rising ocean. A new study by *Wang et al. (2022a)* exploited ECCO's adjoint capability to perform attribution analysis, with applications to sea level variation with respect to the heat and freshwater fluxes – both of which are related to the ocean's buoyancy – along with winds. Having similar mathematical underpinning as the deep learning machine learning methods, ECCO's adjoint capabilities allow to separate the contribution of each forcing both in space (near or far) and time (with lead times of months to years). Focusing on the Nantucket Sound as the geographic center and a proxy for the US east coast, *Wang et al. (2022a)* concluded that the wind contribution is primarily near-local, from regions northeast of Nantucket along the New England shelf. Buoyancy-related contributions from heat and freshwater are overall smaller than wind contributions, but can be comparable to wind contributions in some years. In particular, heat and freshwater flux contributions from the subpolar North Atlantic can affect Nantucket sea level a few years later. This provides an important source of predictability for Nantucket and US east coast sea level.

Projections of relative sea level rise from NASA 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 goals of the team are to transcend barriers among different geoscience disciplines, to develop integrated views of sea level both today and in the future, and to make our latest discoveries useful to the public and decision makers (*Vinogradova and Hamlington 2022*). To translate scientific information so it's useful and available to those who need it, from national, state, and local planners to interested individuals, N-SLCT partnered with the IPCC and launched a data delivery and interpretation platform (https://sealevel.nasa.gov). As the first data-delivery partnership between the IPCC and a US Government Agency, N-SLCT open-source platform lets users explore potential changes in future sea level across the globe as well as coastal flooding at more than 90 coastal sites around the United States (https://sealevel.nasa.gov). As a convenient way to translate the underlying physical mechanisms contributing to the observed and projected sea sea level rise, N-SLCT tools were prominently featured in various climate forums, including the UN COP26, Our Ocean Conference, the White House Climate Task Force, and others.

Another major milestone for N-SLCT was the production of Agency's first scenarios projecting mean sea level rise around the U.S. coastline from decades to a century in the future. The scenarios are based on a suite of climate model projections, combined using a probabilistic framework known as the Framework for Assessing Change to Sea Level, or FACTS that was used by AR6 IPCC. FACTS, which was developed in part through N-SLCT efforts, combines input from models of the different processes that contribute to sea level, such as projections of ice sheet melt and projections of changing ocean dynamics. The scenarios show that sea level along U.S. coastlines will rise 25-30 cm on average above today's levels by 2050. NASA's hot-off-the-press sea level scenarios, observational comparisons, and the science behind them have already demonstrated their impact by forming the basis of the National Assessment of regional sea level rise (*Sweet et al., 2022*). This report was supported by multiple federal agencies as part of the White House Subcommittee on Ocean Science and Technology (SOST) and the U.S. Global Change Research Program (USGCRP), and represent a major advance in planning guidance due to its focus on the near-term time period (now to 2050) and the use of tide gauge and satellite observations in combination with modeled scenarios.

A critical N-SLCT study accompanied the national national sea level assessment is the study by *Nerem et al. (2022)*, who extended the trajectory of the near 30-year satellite altimeter record of global mean sea level into the future and compared it to modeled projections of future sea level rise. This comparison allows planners to understand the current pathway of sea level rise and which future scenario may be most applicable in the coming decades.

Since the release in 2022 of the agency's first projected scenarios for sea level rise, N-SLCT members continue revealing new physical mechanisms and interactions in the climate system, suggesting the potential limitations and incompleteness of our projections. For example, *Piecuch et al (2022)* demonstrated that atmospheric rivers can lead to high-tide flooding along the U.S. west coast. This study highlights the relevance of atmospheric rivers to coastal impacts and flooding and demonstrates the importance of including their influence in predictions. *Dangendorf (2021)* concluded that the change in ocean dynamics is the dominant driver of sea level variability in coastal regions around the world, meaning that continued ocean observing is key to addressing coastal flooding now and in the future. Another recent study by *Li et al. (2022)* developed a new database explaining how different processes impact sea level and water levels, focusing on high-tide flooding events along the U.S. coastlines. Besides sea level rise, the study finds that ocean tides are the main driver for high-tide flooding along the U.S. west coast, while surges are relatively more important along the U.S. east coast. Improved representation of the underlying physical mechanisms has the potential to improve existing high-tide flooding forecasting tools, including those developed by N-SLCT.

The Integrated Earth System & Modeling

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

Climate modeling advances

The atmospheric river (AR) response to Arctic sea ice loss in the Northern hemisphere winter was investigated in Ma et al. [2021] using simulations from the Polar Amplification Model Intercomparison Project. Results showed that the midlatitude responses are dominated by dynamic effects. Poleward of around 60N, the dynamic and thermodynamic effects cancel each other, resulting in relatively small responses. The response uncertainty can be characterized by leading uncertainty modes, with the responses over the Pacific and Atlantic projecting onto a northeastward extension and an equatorward shift mode, respectively. In addition, the responses seem to be mean state-dependent: under the same forcing, models with more poleward-located climatological ARs tend to show stronger equatorward shifts over the Atlantic; over the Pacific, models with more westward-located climatological AR core tend to show stronger northeastward extensions. These relationships highlight the importance of improving the AR climatology representation on reducing the response uncertainty to Arctic sea ice loss.

Chemistry/climate modeling advances

The NASA Goddard Earth Observing System (GEOS) Composition Forecast (GEOS-CF) provides recent estimates and 5-day forecasts of atmospheric composition to the public in near-real time. To do this, the GEOS Earth system model is coupled with the Harvard University GEOS-Chem tropospheric-stratospheric unified chemistry extension (UCX) to represent composition from the surface to the top of the GEOS atmosphere (0.01 hPa). Knowland et al. [2022] described and evaluated the GEOS-CF system, including updates made to the GEOS-Chem UCX mechanism within GEOS-CF for improved representation of stratospheric chemistry. Comparisons were made against balloon, lidar, and satellite observations for stratospheric composition, including measurements of ozone (O3) and important nitrogen and chlorine species related to stratospheric O3 recovery. Overall, the spatial patterns of the GEOS-CF simulated concentrations of stratospheric composition agree well with satellite observations. However, there are some biases—such as low NO*x* and HNO3 in the polar regions and generally low HCl throughout the stratosphere—and future improvements to the chemistry mechanism and emissions will be the subject of continuing work. GEOS-CF is a new tool for the research community and instrument teams observing trace gasses in the stratosphere and troposphere, providing near-real-time three-dimensional gridded information on atmospheric composition.

Near-term climate forcers (NTCFs), including aerosols and chemically reactive gasses such as tropospheric ozone and methane, offer a potential way to mitigate climate change and improve air quality — so called "win-win" mitigation policies. Prior studies support improved air quality under NTCF mitigation, but with conflicting climate impacts that range from a significant reduction in the rate of global warming to only a modest impact. Allen et al. [2021] used state-of-the-art chemistry-climate model simulations conducted as part of the Aerosol and Chemistry Model Intercomparison Project (AerChemMIP) to quantify the 21st-century impact of NTCF reductions, using a realistic future emission scenario with a consistent air quality policy. Non-methane NTCF (NMNTCF; aerosols and ozone precursors) mitigation improves air quality, but leads to significant increases in global mean precipitation of 1.3% by mid-century and 1.4% by end-of-the-century, and corresponding surface warming of 0.23 and 0.21 K. NTCF (all-NTCF; including methane) mitigation further improves air quality, with larger reductions of up to 45% for ozone pollution, while offsetting half of the wetting by mid-century (0.7% increase) and all the wetting by end-of-the-century (non-significant 0.1% increase) and leading to surface cooling of -0.15 K by mid-century and -0.50 K by end-of-the-century. This suggests that methane mitigation offsets warming induced from reductions in NMNTCFs, while also leading to net improvements in air quality.

Climate prediction advances

Lee et al. [2022] successfully demonstrated an ability to accurately forecast spring-summer carbon uptake at multi-month leads. During boreal spring, skillful forecast of Gross Primary Productivity (GPP) was found in northwestern North America, eastern Europe and parts of east-central Asia, where the snowpack removal date was also well predicted. Snowpack initialized in winter remained undisturbed on the surface until the spring snowmelt season, and the information contained in the initial snowpack provides a latent predictability to the climate system, helping determine when the snow will finally melt away and spring vegetation growth and carbon uptake can begin. While these regions extract skillful carbon forecast from accurate forecasts of snowpack removal, other regions such as southeastern Europe extract the skill from the initialization of carbon and nitrogen states.

Over the last two decades, southwestern North America (SWNA) has been in the grip of one of the most severe droughts of the last 1,200 years, with one third to nearly one half of its severity attributable to climate change. Cook et al. [2021] analyzed how the risk of extreme soil moisture droughts in the SWNA, analogous to the most severe 21-year (≥ in magnitude to 2000-2020) and single-year (≥ in magnitude to 2002) events of the last several decades, changes in projections from Phase 6 of the Coupled Model Intercomparison Project. By the end of the 21st century, the SWNA experiences robust ($R \geq 0.80$) soil moisture drying and substantial increases in extreme single-year drought risk that scale strongly with warming, spanning an 8%-26% probability of occurrence across +2-4 K. Notably, the results show that 21-year droughts analogous to 2000-2020 are up to 5 times more likely than extreme single-year droughts under all levels of warming (≈50%). These high levels of 21-year drought risk are largely invariant across scenarios because of large spring precipitation declines in half the models, shifting the SWNA into a drier mean state. Despite projections of this sweeping and ostensibly inevitable increase in 21-year drought risk, climate mitigation reduces their severity by reducing the magnitude of extreme single-year droughts during these events. The results emphasize both the importance of preparing SWNA for imminent increases in persistent drought events and constraining projected precipitation uncertainty to better resolve future long-term drought risk.

Nazarenko et al. [2022] described the response to anthropogenic forcing in the GISS-E2.1 climate models for the 21st century Shared Socioeconomic Pathways emission scenarios within the Coupled Model Intercomparison Project Phase 6 (CMIP6). The experiments were performed using an updated and improved version of the NASA Goddard Institute for Space Studies (GISS) model that included two different versions for atmospheric composition. Each atmospheric version was coupled to two different ocean general circulation models. The global mean responses for all future scenarios and spatial patterns of change for surface air temperature and precipitation for four scenarios were examined: SSP1-2.6, SSP2-4.5, SSP4-6.0, and SSP5-8.5. By 2100, global mean warming ranges from 1.5°C to 5.2°C relative to preindustrial mean temperature. Two high-mitigation scenarios SSP1-1.9 and SSP1-2.6 limit the surface warming to below 2°C by the end of the 21st century. For the high emission scenario SSP5-8.5, the range is 4.6-5.2°C at 2100. Due to about 15% larger effective climate sensitivity and stronger transient climate response in the CMIP6 models compared to CMIP5 versions, there is a stronger warming by 2100 in the SSP emission scenarios than in the comparable Representative Concentration Pathway (RCP) scenarios in CMIP5. Changes in sea ice area are highly correlated to global mean surface air temperature anomalies and show steep declines in both hemispheres, with the largest sea ice area decreases occurring during September. Both coupled models project decreases in the Atlantic overturning stream function by 2100. The largest decrease of 56%-65% in the 21st century overturning stream function is produced in the warmest scenario SSP5-8.5, comparable to the reduction in the corresponding CMIP5 GISS-E2 RCP8.5 simulation. Both low-end scenarios SSP1-1.9 and SSP1-2.6 also simulate substantial reductions of the overturning (9%-37%) with slow recovery of about 10% by the end of the 21st century, relative to the maximum decrease at the middle of the 21st century.

Volcanic flood basalt eruptions have been linked to or are contemporaneous with major climate disruptions, ocean anoxic events, and mass extinctions throughout at least the last 400 M years of Earth's history. Previous studies and recent history have shown that volcanically-driven climate cooling can occur through reflection of sunlight by H_2SO_4 aerosols, while longer-term climate warming can occur via CO_2 emissions. Guzewich et al. [2022] used the Goddard Earth Observing System Chemistry-Climate Model (GEOS CCM) to simulate a 4-year duration volcanic SO_2 emission of the scale of the Wapshilla Ridge member of the Columbia River Basalt eruption. Brief cooling from H_2SO_4 aerosols is outweighed by dynamically and radiatively driven warming of the climate through a three orders of magnitude increase in stratospheric H_2O vapor. While a speculative study, the GEOS CCM is routinely calibrated against observations. The recent Hunga-Tonga eruption bears similarities to the simulated eruption in that it also injected relatively large amounts of water vapor into the stratosphere.

Section 1.1.9.4 Earth Surface and Interior Focus Area

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

Geohazards

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

Earthquakes

Identifying the methods for monitoring and measuring earthquakes and the seismic cycle are useful in mitigating and forecasting future events. In the past year, several researchers have made developments in understanding some of the processes that govern the occurrence rate and magnitude of earthquakes, improving our forecasting abilities. Dutilleul et al. (2022) continue their studies into using periodicity analysis of annual hydrological, atmospheric, thermal, and tidal loadings cycles in relation to earthquake analysis occurrence and hypocenter location in central California. They note that although deeper earthquakes present no semiannual and a weak annual periodicity, some earthquakes exhibit different periodicities in monthly numbers over 1994–2002 and 2006–2014. The authors suggest this indicates a changed distribution of earthquake occurrence within the year after 2003–2005, which may be caused by a weakened Spring peak of pore pressure or altered permeability conditions due to the recent mainshocks. Rundle et al. (2022) seek to provide a review of new approaches to forecasting and nowcasting earthquakes. They provide two general approaches that have been used to forecast earthquakes, using the rate of motion accumulating across faults and the amount of slip in past earthquakes to infer where and when future earthquakes will occur and the using expected pre-earthquake shaking to identify potentially observable changes in the Earth that precede earthquakes. Both of these approaches have limitations and have yet to be used to successfully forecast an earthquake. However, the authors hypothesize that new types of data, models, and computational power may provide avenues for progress using machine learning that were not previously available to predict earthquakes. They also comment that due to the large societal benefit forecasting an earthquake would provide, research in this topic will continue. With the data currently available, the authors argue that there may be more benefit to rapidly characterizing earthquake after they occur than anticipating a rupture just before it occurs.

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. Galetto et al. (2022) published in Nature to demonstrate how eruptions can be forecast by magma flow rates. They show that magma inflow rate, derived from surface deformation, is an indicator of the probability of magma transfer towards the surface, and thus eruption, for basaltic calderas. They also demonstrate that surface deformation alone is a weak precursor of eruption but estimating magma inflow rates by incorporating a viscoelastic model where the relaxation timescale controls whether the critical overpressure for dyke propagation is reached or not provides improved forecasting at basaltic calderas. This has the potential to substantially enhance our capacity of forecasting weeks to months ahead of a possible eruption. Ramsey et al. (2022) discuss the benefits of an orbital volcano observatory and its implication for forecasting eruption timing and scale. They argue that until a sensor with an appropriate orbit configuration and suitable wavebands, gain settings, and spatial resolution for volcano monitoring becomes available, volcanologists will be limited to IR data designed for other science applications and returns will be limited by the instruments available. They hypothesize that a paradigm-shift in spaceborne volcanology will only come about if a dedicated orbital IR volcano observatory is launched in the next decade and that hypertemporal IR data with improved spectral and spatial resolutions are required to analyze ongoing dynamic processes such as the mass flux rates feeding plumes and flows.

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. Geertsema et al. (2022) described and modeled a recent large landslide that led to a tsunami, outburst flood, and sediment plume in the Coast Mountains, British Columbia, Canada on November 28, 2020. They identified how glacial retreat can cause such landslides, which can be followed by cascading hazards. They developed a physical model to forecast the likelihood of a similar event in the future. These physically based models can simulate the hazard cascade, and such models could be used to improve hazard and risk assessments of these events under future climate change.

<u>Section 1.1.9.5</u> 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.

<u>Surface Water</u>

As we saw in Section 1.1.8, WEC is investing in improving our ability to resolve surface water and measure river discharge, especially as we prepare for the upcoming SWOT Mission. Both are important topics to pursue and to stay current with the advances in land modeling efforts that have moved from a traditional climate paradigm, which disregards horizontal movement of water, to one that models surface processes more comprehensively and at higher spatial resolutions. As our models become more sophisticated, they will begin forecasting key surface water parameters such as dynamic runoff routing, snowmelt and river discharge, and lake levels.

Understanding downstream hydrologic impacts for better planning and management of water resources is important as dam construction rises in developing countries. The Biswas *et al.* (2021: *<u>Environmental Modelling & Software</u>*) study develops a global reservoir monitoring framework as an online tool for near real-time monitoring and impact analysis of existing and planned reservoirs based on publicly available and global satellite observations. The framework used a mass balance approach to monitor 1598 reservoirs. Simulated streamflow of the developed tool was validated in 25 river basins against a multidecadal record of in-situ discharge. The simulated storage change was validated against in-situ data from 77 reservoirs. The framework was able to capture reservoir state realistically for more than 75% of these reservoirs. At most in-situ gaging locations, the reservoir tool was able to capture streamflow with a correlation of more than 0.9 and a normalized root mean square error of 50% or less. This tool can now be used to study existing or planned reservoirs for short and long-term decision making and policy analysis.

Extreme Weather and Related Hazards

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

The following two publications contribute to better understanding of river floods and compound hazard events. Pan *el al.* (2021: *Bulletin of the American Meteorological Society*) developed a 3-hourly river discharge record database with 2.94 million river reaches globally over the 40-yr period of 1980–2019. Flood events (above 2-yr return) and their characteristics (number, spatial distribution, and seasonality) were extracted and studied. Validations against 3-hourly flow records from 6,000+ gauges in CONUS and daily records from 14,000+ gauges globally show good modeling performance across all flow ranges, good skills in reconstructing flood events (high extremes), and the benefit of (and need for) subdaily modeling. Raymond *et al*. (2022: *Environmental Research Letters*) study considers projected changes in compounding hazards (hazards occurring close enough to one another to result in amplified impacts) using the Max Planck Institute Grand Ensemble under a moderate (RCP4.5) emissions scenario, which produces warming of about 2.25 °C between pre-industrial (1851–1880) and 2100. The authors find that extreme heat events occurring on three or more consecutive days increase in frequency by 100%–300%, and consecutive extreme precipitation events increase in most regions, nearly doubling for some. The chance of concurrent heat and drought leading to simultaneous maize failures in three or more breadbasket regions approximately doubles, while interannual wet-dry oscillations become at least 20% more likely across much of the subtropics. The results highlight the importance of taking compounding climate extremes into account when looking at possible tipping points of socio-environmental systems.

Water Availability

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

For example, in Mohammed *et al.* (2022: *Scientific Reports*), water management across transboundary river basins is considered, specifically how climate change and dam development could impact the Se Kong, Se San and Sre Pok rivers in the Mekong region.. The authors demonstrate an integrated approach to exploring these issues through the lens of a social-ecological system, combining remote and in-situ earth observations, hydrologic and climate models, and social surveys. The researchers find that climate change will lead to increased precipitation, necessitating a shift in dam operations, from maintaining low flows to reducing flood hazards. They also find that existing water governance systems in Laos, Vietnam, and Cambodia are ill-prepared to address the problem. Unless major deficiencies in transboundary water governance, strategic planning, financial capacity, information sharing, and law enforcement are remedied, the ability to address complex issues will be highly constrained.

Dezfuli *et al.* (2022: Earth's Future) also look at climate change impacts on transboundary water issues and include a socio-environmental lens. Climate model projections show that the adverse effects of extreme climate events will likely be exacerbated over downstream countries of the Tigris-Euphrates basin in coming decades. This conclusion is drawn because concurrent extreme hot and dry conditions and enhanced precipitation variability are projected over the Tigris-Euphrates headwaters, where the Southeastern Anatolia Project is located. As a result, the negative impacts of the project (exacerbating existing environmental, agricultural, water conflict, and public health issues) may outnumber its benefits, and this study attempts to warn decision-makers of the urgent need to integrate these trends to water resource planning and international negotiations.

<u>Section 1.1.9.6</u> 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.

The following sections describe the progress made in the past year (2021-2022).

<u>Development and Application of Data Assimilation Systems</u>

<u>Joint Effort for Data Assimilation Integration (JEDI) Development</u>: The Joint Center for Satellite Data Assimilation (JCSDA) is spearheading the Joint Effort for Data assimilation Integration (JEDI) project to build an integrated data assimilation system for the modern era (Auligné, 2021). It harnesses generic programming and object-oriented design practices to build scientific software that is efficient, flexible and easy to use (Auligné, 2022). Data assimilation algorithms are built in a generic way to be usable across centers and thus mutualize the effort for software development and maintenance (Liu et al., 2022). NASA has embraced the JEDI project as a way to advance the science of data assimilation for its Global Earth Observing System (GEOS) model and build a system capable of scaling to NASA's ambitious future plans, such as coupled Earth system data assimilation.

The JCSDA has coordinated a team of scientists from multiple agencies on the development of the JEDI Unified Forward Operator (UFO), which computes observation-equivalent quantities from numerical model forecasts. The novelty of the approach in the UFO comes from the separation of concerns within the software to insulate observation-related code from other components that are model-specific. Hence, the UFO can be developed in parallel and used by a variety of teams working on different systems. This has been greatly facilitated through the development and adoption of JEDI observation data conventions (https://jointcenterforsatellitedataassimilation-jedi-docs.readthedocs-hosted.com/en/latest/inside/conventions/index.html). Over the course of this year, the JCSDA and partners have made significant progress toward the goal to support an extensive suite of satellite and conventional instruments. In particular, the UFO is able to match most capabilities within the GSI data assimilation (Martin et al., 2021), and provide novel capabilities such as geostationary hyperspectral sounders (Han et al., 2021).

<u>Sea-ice Ocean and Coupled Assimilation (SOCA) Development</u>: JCSDA and Global Modeling and Assimilation Office (GMAO) scientists have collaborated on the assimilation of surface sensitive microwave and infrared radiances and on the implementation of coupled atmosphere/ocean/sea-ice data assimilation capability within the JEDI framework. JCSDA has been working on the direct radiance assimilation of surface sensitive radiances focusing on GMI and Advanced Very-High-Resolution Radiometer (AVHRR) for the Sea Surface Temperature (SST) Constraint and Soil Moisture Active Passive (SMAP) for the Sea Surface Salinity (SSS) constraint. Recently the implementation of the Ocean Color Forward Operator (OASIM) has started inside the

JEDI Unified Forward Operator, which will be used for the assimilation of Ocean color instruments such as MODIS and Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission that will continue and advance observations of global ocean color.

In November 2021, JCSDA announced the first public release of its JEDI-based marine data assimilation (https://www.jcsda.org/soca), which provides everything that is needed for ensemble and variational data assimilation applications for the Modular Ocean Model version 6 (MOM6). This JEDI-SOCA release also includes a complete set of marine observation operators. JEDI-SOCA was developed by the JCSDA with contributions from GMAO and NOAA. It is currently used to initialize the ocean and sea ice component of the GEOS at GMAO, and the ocean, sea ice, and wave component of the Unified Forecast System at NOAA.

Toward Coupled Earth System Data Assimilation: In July 2022, JCSDA distributed to the community the JEDI-SkyLab 1.0 roll-up release (https://www.jcsda.org/jediskylab) that provides the first 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 atmosphere, ocean, soil moisture, snow, and aerosols. This release represents an important step to bridge research and operations since it introduces a) SkyLab flagship application (https://skylab.jcsda.org) to focus and demonstrate joint development toward future operational deployments; b) a turnkey ecosystem for the community to easily reproduce SkyLab on multiple high-performance computing platforms including NASA's Discover and AWS; and c) automated testing of SkyLab new functions for rapid prototyping.

Observation Impact and Information Retention in the Lower Troposphere in the GMAO GEOS Data Assimilation System: To prepare for future observing systems of the next decade and set the stage for follow-on PBL studies, Zhu et al. 2022 has assessed the effectiveness of the use of existing observing systems in the lower troposphere in the GEOS system through forecast-based sensitivity observation impact (FSOI) and a set of data denial observing system experiments. The results show that microwave radiances and conventional data are the two most important data types to improving model forecast skills in the lower troposphere.

Sensitivity of Low Tropospheric Arctic Temperatures to Assimilation of AIRS Cloud-cleared Radiances: Impact on Mid-latitude Waves: The improved capability to predict weather and its extreme events is a high priority for WAD. Work published by McGrath-Spangler et al. (2021) showed that forecasts of midlatitude weather may be improved by assimilating cloud-cleared AIRS radiances in dynamically active north polar regions that are otherwise under-observed due to frequent low-level cloud cover. The improvement stems from a more accurate representation of the Arctic low tropospheric thermal structure, which in turn affects geopotential gradients in the mid-troposphere. This work builds off previous efforts that showed improved representation of tropical cyclones (Reale et al. 2018) and polar lows (Ganeshan et al., 2022) using a similar approach. Assimilation of cloud-cleared infrared radiances applies NASA remote sensing expertise to permit ingestion of atmospheric measurements that are normally discarded when clouds are present. An added benefit of this work is that it progresses toward a readiness to assimilate cloud-affected data from current and future hyperspectral infrared spectrometer instruments such as CrIS.

Assimilation of SMAP Brightness Temperature Observations in the GEOS Land-Atmosphere Data Assimilation System: Reichle et al. (2021) assimilated brightness temperature (Tb) observations from the SMAP mission in the GEOS weather analysis during boreal summer 2017. The study finds that the SMAP Tb assimilation improves the skill of soil moisture estimates compared to a system without SMAP assimilation. Consequently, screen-level specific humidity and daily maximum temperature also improve, in some regions by up to 0.4 g/kg and 0.3 K, respectively. Results demonstrate the potential of SMAP Tb observations for improving global operational weather analysis and forecasting systems.

pyCRTM: A Python Interface for the Community Radiative Transfer Model: The Community Radiative Transfer Model (CRTM) provides fast simulations of what visible, infrared and microwave instruments observe in orbit. An example of such a simulation would be an image of cloud cover observed from a satellite instrument. The CRTM provides a fast tool for satellite remote sensing applications; however, its Fortran interface is difficult for those less well versed in Fortran. In Karpowicz et al., 2022, pyCRTM was developed to wrap CRTM in a more modern language widely used by scientists and students known as Python. The goal of pyCRTM is to lower the barrier of entry for university students to learn and use the CRTM and to boost the productivity of researchers seeking to create new methods in utilizing satellite data without having to go through the pre-existing complexity of the CRTM Fortran interface.

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. An Observing System Experiment (OSE) was performed to assess the impact of CYGNSS wind products on storm track, maximum sustained wind speed (aka intensity), and minimum sea level pressure (MSLP) forecasts. The OSE examined forecast skill in the period leading up to the rapid intensification phase of Hurricane Michael in 2018 (Mueller et al., 2021). Hurricane Michael is noteworthy for the relatively poor quality of the operational prediction made by the National Hurricane Center of its rapid intensification. This is clearly indicated by the control case considered in the OSE, which replicated the operational prediction and shows a significant increase in the error in intensity and MSLP during rapid intensification. The forecast with assimilation of CYGNSS data included, on the other hand, shows a marked improvement, with errors in both intensity and MSLP being much lower during the rapid intensification phase. The storm track forecast was also improved somewhat, but not significantly.

Exploring Trends in Tropical Cyclone Rainfall: Tropical cyclones represent a major hazard due to wind, storm surge and precipitation. Warming ocean and atmospheric temperatures associated with climate change are expected to increase the potential intensity of tropical cyclones and the amount of moisture that storms can hold, raising the prospect that tropical cyclones may eventually produce greater volumes of rainfall. In Guzman and Jiang (2021a), 19 years of TRMM and GPM rainfall information are examined to explore trends in tropical cyclone rainfall. They find a trend of 1.3% per year for average tropical cyclone rainfall, primarily associated with increases in rainfall in the outer rainbands rather than the inner core region (e.g., eyewall). The trends are most pronounced in the northern Pacific and Atlantic basins and show little dependence on storm intensity.

Assessing the Impacts of Incorporating Satellite Data in All-Sky Conditions for Hurricane Forecasting: Recent years have seen increased efforts to incorporate satellite information in all-sky conditions rather than in clear or non-raining areas. Zhang et al. (2021) examined the impacts of assimilating all-sky passive microwave brightness temperatures from sensors like the GMI, in combination with GOES infrared radiances, on forecasts of Hurricane Harvey (2017) using the WRF model. They found that the assimilation of the combination of GMI reduced forecast errors for storm track and intensity, including rapid intensification and peak intensity compared to a simulation without the data. Assimilation of the precipitation-impact GMI brightness temperatures also improve the representation of storm precipitation structure and rainfall.

Advancing the Prediction of Precipitation

Validating Rainfall Predictions from Global Climate Models: The TRMM and GPM measurements have provided excellent benchmarks for the validation of rainfall from global climate models, not only in terms of the distribution and intensity of rainfall, but also in terms of the diurnal cycle of precipitation. Tang et al. (2021) examine the diurnal cycle of the latest Climate Model Intercomparison Project (CMIP6) models for the period 1996-2005 and compare the simulated results to multiple satellite and ground-based estimates. They find that the models contain a diurnal phase that is 3-4 hours earlier than in observations over land and 1-2 hours earlier over oceans. The errors are reduced from those seen with the CMIP5 models. They attribute the improvement to improved parameterizations of convection. Most models are also unable to capture the nighttime peak in precipitation associated with elevated convection and propagating convective systems.

Assimilating IMERG Rainfall Estimates into a Coupled Land-Atmosphere Model: Yi et al. (2021) assimilate IMERG rainfall estimates into a coupled land-atmosphere model based on the WRF model and the TOPX hydrological model. The assimilation of IMERG data reduced overestimations of precipitation and evaporation and improved estimates of soil moisture and water discharges.

Improved Understanding and Modeling of Convective Cloud Size: How large a convective system grows is important for understanding rainfall accumulation and impacts on Earth's radiation. Vertical mass fluxes in thunderstorm cores drive growth, but mass flux is not observable from space. Elsaesser et al. (2022) address the question: Can a mass flux proxy be developed and used to understand and predict overall system sizes? Atmospheric stability computed from AIRS temperature and humidity, as well as GPM thunderstorm latent heating, are used to develop an equation that serves as a proxy for storm mass flux. The equation is incorporated into a simple model that predicts system size variations that agree with geostationary satellite estimates. Improved equations for convective system sizes can be used in climate models to better predict changes in storm rainfall and cloud radiative effects that drive climate projections.

Assessing the Impact of the Madden-Julian Oscillation (MJO) on Extreme Precipitation: The MJO is a 30 - 90 day mode of variability in the tropics that strongly impacts precipitation occurrence and intensity in the region of Southeast Asia. Da Silva and Matthews (2021) looked at the impact of the MJO on the occurrence of extreme precipitation using 19 years of GPM IMERG data. They found that the probability of experiencing extreme precipitation more than doubled during some phases of the MJO and decreased by half in other phases. The spatial pattern of these extremes is strongly influenced by the complex distribution of land in the region. They also found that extreme rainfall over the Maritime Continent could be tied to amplification of the diurnal cycle.

Comparing the Performance of IMERG to Six Other Satellite Precipitation Products for Flood Simulation and Prediction: Hinge et al. (2022) conducted a literature review to assess and compare the performance of IMERG to six other satellite precipitation products (CHIRPS, Climate Prediction Center Morphing Technique [CMORPH], Global Satellite Mapping of Precipitation [GSMaP], Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks [PERSIANN], PERSIANN Climate Data Record [CDR], and TRMM Multi-Satellite Precipitation Analysis [TMPA]) for flood simulation and prediction across the globe, and under different settings: climate zone, topography, and within different hydrological models. CMORPH, IMERG, and TMPA performed better than the other products for flood simulation and forecasting under diverse settings. This indicates the advantages of using algorithms that combine measurements from different sensors for flood applications.

Evaluating the Ability of IMERG Products to Simulate Flood Events: Ouaba et al. (2022) examined the ability of IMERG products to simulate flood events in the ungauged Bourrous basin in Morocco by using the Soil Conservation Service–Curve Number (SCS-CN) model. They first applied this simulation in a nearby gauged basin (the Ghdat basin in Morocco) in order to validate it over a 17-year period. Results suggest that IMERG early and final products show an underestimation of both the peak flow and the volume between simulated discharges and observations at the Ghdat basin gauge station. The study concludes by computing the discharge for the Bourrous basin from IMERG early and final products to illustrate their utility for the estimation of flow rates in ungauged basins across Morocco.

Developing a Tropical Precipitation and Flood Inundation Mapping Framework: Tew et al. (2022) developed a Rapid Extreme TRopicAl preCipitation and flood inundation mapping framEwork (RETRACE) by utilizing: (1) Google Earth Engine (GEE); (2) GPM IMERG-L to perform spatial and temporal analysis of precipitation; (3) Sentinel-1 SAR and Sentinel-2 optical satellites; and (4) flood victim information. The framework was demonstrated and validated against the Dec 2021– Jan 2022 Malaysia flood event. Precipitation was slightly underestimated using IMERG-L compared to ground data. Overall, the result shows that the presented framework could produce flood inundated maps at 62-70% accuracy with the threshold values suggested in the study. RETRACE can be a useful tool in helping local authorities for use in flood management and to compare with the flooded areas simulated using flood models.

Improving Precipitation Accuracy of TRMM and GPM Multi-Satellite Products over the Langat Basin River: Soo et al. (2022) investigated the capability of both quantile mapping (QM) bias correction and kriging merging techniques to improve precipitation accuracy of TRMM and GPM multi-satellite products over the Langat River Basin in Malaysia. Findings show that QM first, followed by kriging merging (QK-TRMM and QK-IMERG), give significant improvement in almost all aspects of rainfall and streamflow comparisons. The study also performed streamflow simulation with the hydrological modeling system (Hydrologic Engineering Center Hydrologic Modeling System [HEC-HMS]) to validate the performance of raw and enhanced satellite estimations for the 2014–2015 extreme flood events. Both QK-TRMM and QK-IMERG show great improvement in the overall streamflow simulation. The results reveal that the newly proposed bias correction method, namely merging the QM and kriging methods, can contribute to the improvement of precipitation estimation, benefiting water resources planning and flood forecasting.

Developing a Landslide Susceptibility Map Along the China-Pakistan Economic Corridor (CPEC) Route: Maqsoom et al. (2021) created a landslide susceptibility map along the CPEC route using 13 landslide causative factors. These included interpolated IMERG rainfall data, elevation, slope, lithology, drainage intensity, Normalized Difference Water Index (NDWI), structural fault, land use, earthquake hazard, Normalized Difference Vegetation Index (NDVI), aspect, soil type, and plan curvature. The causative factors were weighted according to their potential for developing a landslide event in a pairwise matrix of a multi-criteria decision-making approach. Results indicate that soil type (17%), slope (16%), rainfall (16%), and NDWI (11%) were found to be more prominent conditioning factors for landslides. The results indicated that about 38% of the study area falls under the categories of high and very high susceptibility.

Comparing Global Precipitation Model Analyses with Global Satellite Analyses: Global precipitation analyses are critical to many applications related to agriculture, flood and landslide monitoring, power generation, among others. In this study, Xu et al. (2022) assess whether global model analyses from the European Center for Medium Range Forecasts perform as well as, or better than, global satellite analyses of rainfall such as from IMERG or GSMaP. Using four years of data, they find that the satellite analyses tend to perform better than the models, with the exception of high latitude regions and during winter months where and when frozen precipitation tends to occur frequently. Between the two satellite analyses, IMERG tends to perform best while GSMaP tends to overestimate precipitation.

Examining the Japanese Operational Weather Forecast System: Ikuta et al. (2021) compared data from the GPM DPR and GMI to simulations of precipitation systems using the Japanese operational weather forecast system, finding that the model produced too little cloud ice, too much graupel, and too little low-level rainfall. They explored changes to the cloud microphysics scheme using a single column model and determined that the insufficient amount of cloud ice was due to an overly aggressive conversion of ice to snow at upper levels and that the underprediction of rain at lower levels was caused by prescribing an excessive number of small-diameter raindrops.

Analysis of Lightning Data

Examining Mesoscale Convective Systems (MCSs) Relative to Peak Lightning Activity: Hayden et al. (2021) use GPM Precipitation Feature (PF) data and IMERG data, along with a convective system tracking algorithm, to examine MCSs over their lifetimes. The life cycles of the storms are composited relative to the period of peak lightning activity. They find that the height of the 20-dBZ echo tends to peak at the time of maximum lightning occurrence while the stratiform rain volume tends to be minimum at this time, with echo top heights decreasing and stratiform volume increasing after the peak in lightning. The study also examines differences in the latent heating profile between tropical and extratropical precipitation systems.

Improving the Atmospheric Models and Prediction

AIRS and Intergovernmental Panel on Climate Change (IPCC): Sounder observations, in particular AIRS (on the Aqua EOS satellite) data, were used extensively to evaluate the performance of climate models that participated in CMIP6. These models are the foundation for the most recent IPCC Assessment Report (AR6). AIRS was one of the key datasets used in a critical IPCC chapter on climate trends. In general, AIRS data and several AIRS studies were cited numerous times in the latest IPCC report [IPCC 2021].

Constraining Arctic Climate Projections using AIRS: The Arctic is rapidly warming and is most pronounced near the surface during winter, due to a loss in sea ice cover and an increase in surface turbulent fluxes. Currently, there are large climate model errors in sea ice loss, turbulent fluxes, and wintertime warming. This uncertainty hinders our ability to predict future wintertime warming. AIRS surface turbulent fluxes are used to assess CMIP6 models in northern hemisphere (NH) winter, 2002-2020. Climate models capture the general sensitivity of surface turbulent fluxes to declining sea ice and to surface-air gradients of temperature/moisture, but substantial mean state biases exist. Boisvert et al. (2022) show a clear relation between current trends in surface fluxes with projected warming: Models with larger surface trends show larger warming. Using these AIRS trends indicates that Arctic winter warming could fall within 14–17 K.

Investigation of the Potential Saturation of Information from Global Navigation Satellite System Radio Occultation Observations with an Observing System Simulation Experiment: Global Navigation Satellite System (GNSS) Radio Occultations (RO) provide measurements of atmospheric temperature around the globe using the same technology familiar from “GPS” location services. Recently there has been increased interest in substantially increasing the number of GNSS platforms in order to improve weather forecasts. Privé et al. (2022) performed Observing System Simulation Experiments (OSSEs) of the global observing network including the addition of up to 100,000 new GNSS RO temperature profiles per day to evaluate the potential impacts of this new data on numerical weather prediction. They found that incorporating large quantities of RO data resulted in a substantial improvement of the forecast skill, with greatest impact in the first 1-2 days of the forecast, but some significant impact at 5-7 days. The largest impacts were seen in the tropics and Southern Hemisphere Extratropics, where there are fewer in situ observations than in the Northern Hemisphere Extratropics. Some possible suboptimal behavior of the data assimilation system was found when ingesting the RO data, suggesting that efforts to improve the methodology used for RO handling could yield even greater observation impacts.

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