EARTH SCIENCE DIVISION

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<u>Annual Performance Goal 1.1.8:</u> 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.

<u>Section 1.1.8.1</u> Atmospheric Composition Focus Area

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

To demonstrate progress in characterizing the behavior of the Earth system, including its various components and the naturally-occurring and human-induced forcings that act upon it, we report here highlights of ACFA sponsored research published since July 2023 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 inherent in the high temporal and spatial variability of the ground-based air quality networks with a combination of new space-borne measurements well as expansion of ground-based networks

(c) improve estimates of emissions of greenhouse gases CO_2 and methane (CH_4) and others in order to better understand their variability in space and in time

(d) use NASA's portfolio of space-based instruments such as the Ozone Monitoring Instrument (OMI) and the Microwave Limb Sounder (MLS) on the Aura satellite, SAGE-III ISS, the Ozone Mapping Profiler Suite-Limb Profiler on the Suomi-NPP, TEMPO, and EPIC on the DSCOVR satellite and others, together with measurements made by stations in the Network for Detection of Atmospheric Composition Change (NDACC) and its partner networks 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.

Aerosols, clouds and radiative forcing

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

Aerosol formation

New particle formation in the free troposphere is a major source of cloud condensation nuclei globally. The prevailing view is that in the free troposphere, new particles are formed predominantly in convective cloud outflows. Zhang *et al.* (2024) present another mechanism using global observations. They find that during stratospheric air intrusion events, descending ozone-rich stratospheric air mixes with the moister free tropospheric background, resulting in elevated hydroxyl radical (OH) concentrations. Such mixing is most prevalent near the tropopause where the sulfur dioxide (SO_2) mixing ratios are high. The combination of elevated SO_2 and OH levels leads to enhanced sulfuric acid concentrations, promoting particle formation. Such new particle formation occurs frequently and over large geographic regions, representing an important particle source in the midlatitude free troposphere.

Aerosol retrievals

Limbacher et al. (2024) describe MAGARA, a Multi-Angle Geostationary Aerosol Retrieval Algorithm that leverages multi-angle Advance Baseline (ABI) imagery from the GOES-16, -17, and -18 geostationary satellites to exploit the differences in autocorrelation timescales between surface reflectance, aerosol type, and aerosol loading. MAGARA retrieves pixel-level (up to 1 km) aerosol loading and fine-mode fraction at up to the cadence of the measurements (10 min), fine- and coarse-mode aerosol particle properties at a daily cadence, and surface properties by combining the multi-angle radiances with robust surface characterization inherent to temporally tiled algorithms. In three case studies, comparisons of MAGARA *vs*. coincident AERONET indicate good sensitivity to fine-mode fraction over land, especially for smoky regions. Bias-corrected MAGARA vs. coincident AERONET spectral single-scattering albedo are highly correlated as well. MAGARA performs best in regions where surface reflectance varies over long timescales with minimal clouds (*e.g.,* a large portion of the western US), and for these regions, aerosol type and aerosol loading on timescales as short as 10 min could allow for novel research into aerosol–cloud interactions, improvements to air-quality modeling and forecasting, and tighter constraints on direct aerosol radiative forcing.

Aerosol-cloud interaction

Aerosol-cloud interaction (ACI) regulates the energy budget of the Earth and poses the largest uncertainty in climate projection. ACI for low clouds is in particular poorly understood and causes the spread of Earth System Models (ESMs) in predicting cloud and climate responses to aerosol changes. Process studies have shown nonlinear cloud water amount and cloud fraction adjustments due to aerosol changes via precipitation and cloud top entrainment, which are not often captured correctly in ESMs. *Li et al.* (2024) explore the physical mechanisms of ACI in marine low clouds with a focus on precipitating low clouds using a cloud process model and unprecedented field campaign measurements of the meteorological state, cloud properties, and aerosols collected during the **A**erosol **C**loud me**T**eorology **I**nteractions o**V**er the western **AT**lantic **E**xperiment (ACTIVATE). They show that the aerosol-induced cloud water amount adjustment is dominated by changes in precipitation and there is no clear entrainment feedback in either case.

Radiative effects of aerosols

Human activities affect the Earth's climate through modifying the composition of the atmosphere, which then can induce radiative forcings that drive climate change. An example is the cooling effect of anthropogenic aerosols that partially has partially offset the warming effect of anthropogenic greenhouse gases. However, in 2020 fuel regulations abruptly reduced the emission of sulfur dioxide from international shipping by about 80% and created an inadvertent geoengineering termination shock with global impact. *Yuan et al.* (2024) estimate the new fuel regulations led to a radiative forcing of +0.2 ± 0.11 Wm^{-2} averaged over the global ocean. The amount of radiative forcing could lead to a doubling (or more) of the warming rate in the 2020s compared with the rate since 1980 but with strong spatiotemporal heterogeneity. The warming effect is consistent with the recent observed strong warming in 2023 and expected to make the 2020s as a whole anomalously warm. The forcing is equivalent in magnitude to 80% of the measured increase in planetary heat uptake since 2020. The radiative forcing also has strong hemispheric contrast, which has important implications for precipitation pattern changes.

Dynamical and physical properties of clouds

It was recognized in the 2000s that significant difficulties in the simulation of tropospheric ice clouds in climate models were due in part to a lack of high-quality global observations, with perhaps the most critical need being for vertically resolved observations of ice mass. The introduction of active sensors (CALIPSO and CloudSat) to the A-Train provided a major advance in our abilities to observe and characterize ice clouds. *Winker et al.* (2024) describe a new Level 3 CALIPSO ice cloud product (L3-ICE) covering the period 2006-2018. L3-ICE is similar to existing ice cloud products that use combined CALIPSO and CloudSat observations but provides complete temporal coverage of the 2006-2018 period, while the joint products are limited by the daytime-only operation of the CloudSat radar since 2010. All the active sensor IWC retrievals are dependent in one way or another on the ice particle mass-size relations which are used. They compare the extinction and ice-water content (IWC) profiles of L3-ICE with those of two of the available global products based on combined CALIPSO and CloudSat observations, finding significant differences between the three products. These comparisons highlight the importance of obtaining a better understanding of ice particle mass–size relations to reduce uncertainties in these products and bringing them into better agreement.

Even though satellite observations have been used to improve climate model simulations of cloud thermodynamic phase, few studies have validated satellite-based cloud phase distributions on a global scale. *Wang, Yang and Diao* (2024) develop a large data set based on *in situ* aircraft-based observations from 11 flight campaigns in various regions. CALIPSO data show the best comparison results for representing the fraction of ice clouds among all types of cloud phases. CloudSat overestimates mixed phase frequency and DARDAR (raDAR/liDAR) overestimates ice phase frequency, though penetration through cloud layers is better when radar and lidar data are combined. The impacts of seasonal variability, spatial variability among various latitudes and longitudes, as well as temporal variability from a few hours to different seasons are examined. The results of help to identify the key factors affecting cloud phase distributions from a near-global perspective. The methodology developed can also guide future validations of satellite data using aircraft-based observations.

The poor representation of the macrophysical properties of shallow oceanic cumuli in climate models contributes to the large uncertainty in cloud feedback. These properties are also difficult to measure because it requires high-resolution satellite imagery that is seldomly collected over ocean. *De Vera et al.* (2024) examine cumulus cloud macrophysical properties, their size, shape, and spatial distributions, over the tropical western Pacific using 170 15-m resolution scenes from Terra's Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) collected during the 2019 Cloud, Aerosol and Monsoon Processes Philippines Experiment (CAMP^{2}Ex) mission. The average cloud fraction was 0.12, half of which was contributed by clouds less than 1.6 km in area-equivalent diameter. ASTER, Terra’s Multi-angle Imaging SpectroRadiometer (MISR), and CAMP^{2}Ex aircraft lidar showed excellent agreement in the cloud-top height distribution peak altitude of $\sim$ 750 m. They find that the variation in mean cloud-top height is controlled most by the total column water vapor, lower-tropospheric stability (LTS), and estimated inversion strength (EIS). In contrast, variation in cloud is most controlled by surface wind speed and near-cloud relative humidity, suggesting the need to improve low-cloud parameterizations in climate models that use LTS/EIS based on stratocumulus studies.

Past studies of the potential effects of changes in clouds on climate have focused on long-term cloud changes, and the diurnal cycles of cloud properties have been mostly ignored partly owing to the limited availability of global datasets to study higher frequency variabilities. Residing at the Lagrange L1 point, DSCOVR overcomes the temporal limitations of polar orbiters as well as the limited spatial views of geostationary satellites, allowing characterization of the daytime variability of cloud properties using a single sensor. *Delgado-Bonal et al.* (2024) expand on previous studies to investigate the variability of cloud optical thickness, observing a recurring diurnal pattern of cloud optical thicknesses for different latitudinal zones that reaches a maximum around noon regardless of the underlying surface. After separating clouds into optically thin (0–3), intermediate (3–10), and thick (10–25), they find that these cloud classes follow different optical thickness diurnal cycles on the global scale.

Cloud-radiation interactions and feedbacks

Using satellite observations of trends in solar absorption and emitted thermal radiation over the Arctic and Antarctic for the last two decades, *Prince and L'Ecuyer* (2024) show that Arctic thermal emission is increasing at a rate that almost instantly compensates for changes in solar absorption due to reduced sea ice. This rapid adjustment means that the net Arctic energy imbalance has been invariant despite the rapidly warming Arctic climate. Conversely, Antarctic thermal emission is not responding to recent increases in solar absorption demonstrating that Antarctic surface temperatures are not significantly influenced by the region's reflectivity. As a result, changes in energy input in the Antarctic are likely exerting a more substantial influence on poleward heat transport than those in the Arctic.

In the tropics, the shortwave cooling from thick high clouds nearly balances the longwave cooling of thin high clouds in the current climate. But the degree to which this balance is maintained under climate warming is a leading source of uncertainty in recent climate assessments because climate models simulate a wide variety of tropical cloud responses to warming. Thermodynamic arguments predict that the area of thick anvil clouds will decrease with warming but changes in opacity and in the properties of thin high clouds are much more uncertain. *Sokol et al.* (2024) employ data from CALIPSO and CloudSat to assess the cloud radiative feedback in an ensemble of simulations with high-resolution cloud radiative models (CRMs). They find the net tropical high cloud radiative feedback is more dependent on changes in cloud opacity than on changes in high cloud cover, suggesting that tropical high clouds may act to enhance global warming more than has been suggested in recent assessments of the Earth's climate sensitivity.

Loeb et al. (2024) use satellite observations from the Clouds and the Earth's Radiant Energy System (CERES) project to show that Earth's energy imbalance has doubled to 1.0 ± 0.2 W m^{-2} over the past decade relative to the 2000s. This is a result of a 0.9 ± 0.3 W m^{-2} increase in absorbed solar radiation (ASR) that is only partially offset by a 0.4 ± 0.25 W m^{-2} increase in outgoing longwave radiation (OLR). ASR increases in the Northern Hemisphere result from decreased stratocumulus and middle cloud cover over the sub-tropics and decreased coverage by low and middle clouds at mid-latitudes. Over the eastern and northern Pacific Ocean, the reduced cloud cover is associated with large increases in sea-surface temperature (SST). The offsetting OLR increases are due to the decreased cloud cover and higher SSTs. In the Southern Hemisphere OLR changes are weak as ASR increases are due to reduced middle cloud reflection and a weaker reduction in low-cloud reflection. Changes in cloud cover in response to SST increases imply a feedback to climate change yet a contribution from radiative forcing or internal variability cannot be ruled out.

Twenty years of satellite-based cloud and radiation observations provided *Jin et al.* (2024) the opportunity to examine the observed cloud radiative effect (CRE) feedback (*i.e.,* the change in CRE per unit change in global mean surface temperature). By separating the contribution of "internal changes" and "relative-frequency-of-occurrence (RFO) changes" in distinct cloud-regime groups, notable seasonal contrasts of CRE feedback characteristics emerge. Boreal winter CRE feedback is dominated by the positive shortwave CRE feedback of oceanic low-thick clouds, due to their decreasing RFO as temperature rises. This signal is most likely due to El Niño–Southern Oscillation (ENSO) activity. When

ENSO signals are excluded, boreal winter CRE feedback becomes qualitatively similar to the boreal summer feedback. CRE feedbacks in most cloud-regime groups largely come from changing RFO (*e.g.*, the predominant transition from oceanic cumulus to broken clouds and more occurrences of higher convective clouds with warming temperature). At the same time, low-thick and broken clouds experience optical thinning and decreasing cloud fraction, and these features are more prominent in boreal summer than winter. Overall, the seasonally asymmetric patterns of CRE feedback, primarily due to ENSO, introduce complexity in assessments of CRE feedback.

Dust

Dust plays a key role in many Earth system processes and is ubiquitous in the Martian atmosphere as well. Various intensive field campaigns, laboratory analyses, space-based remote sensing missions, and global modeling efforts aim to characterize dust optical properties, and yet the interpretation of retrievals and comparison to models remains complicated by various conflicting assumptions that are part of each algorithm. *Castellanos et al.* (2024) review the assumptions underlying satellite retrieval alogrithms and identify what observations might reduce uncertainties to allow for a more rigorous and harmonious comparisons. They note that the Earth system models surveyed for the paper assume a globally uniform, size-invariant refractive index, though current measurements of the refractive index vary widely. This inhibits attempts to represent variability in dust optical properties and forcing as would be expected from different major dust source regions on Earth. Another outstanding issue is the lack of comprehensive and realistic shape models for dust, such that closure between forward modeling from particle refractive index, shape, and size and observed optical properties cannot be achieved. Field observations indicate the persistence of coarse and giant dust particles at higher altitudes and farther downwind from their source than previously expected, but remote sensing retrieval algorithms based on observations at visible wavelengths have limited sensitivity to these particles. In order to verify the fidelity of simplifying assumptions for refractive index, for example, a chain of measurements is needed, ranging from characterizing individual dust mineralogy to *in situ* sampling of complex atmospheric aerosol mixtures. Such results could be applied to both remote sensing retrievals that characterize the optical properties of the total aerosol burden in the atmosphere from total radiance measurements and to global models that represent the total aerosol burden in the atmosphere.

Tropospheric composition and air quality

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. We summarize nine papers in this subsection spanning a wide range of scientific topics in this broad area of study.

NO_x emissions

Satellite-derived spatiotemporal patterns of nitrogen oxide (NO_x) emissions can improve accuracy of emission inventories to better support air quality and climate research and policy studies. *F. Liu et al.* (2024**)** develop a method to use spatiotemporal patterns of nitrogen oxide (NO_x) emissions derived from TROPOspheric Monitoring Instrument (TROPOMI) measurements of NO_x along with chemical transport modeling to map emissions at high resolution across US cities. The accuracy of the coupled method is validated through application to synthetic NO_2 observations from the NASA-Unified Weather Research and Forecasting (NU-WRF) model. They then develop a TROPOMI-based database reporting annual emissions for 39 US cities at a horizontal spatial resolution of $0.05° \times 0.05°$ from 2018 to 2021. This database demonstrates a strong correlation ($r = 0.90$) with the National Emission Inventory (NEI) but reveals some bias (NMB $= -0.24$). There are noticeable differences in the spatial patterns of emissions in some cities. The analysis suggests that uncertainties in TROPOMI-based emissions and potential misallocation of emissions and/or missing sources in bottom-up emission inventories both contribute to these differences.

Air quality and impacts

Wei et al. (2024) estimate long-term trends in black carbon (BC) and PM2.5 concentrations and their attributable mortality burden across the US. Daily concentrations of PM2.5 and its highly toxic BC component at 1-km resolution from 2000 to 2020 are derived using a deep learning approach that integrates data from MISR, MODIS, chemical transport models, and surface observations. Annual PM2.5-attributable and BC-attributable mortality burden were estimated using concentration–response functions collected from a national cohort study and a meta-analysis study, respectively. The spatiotemporal trends in PM2.5 and BC pollution, the associated premature deaths, and the impact of wildfires on air quality and public health were analyzed. The findings show that long-term improvements in air quality and public health in the continental US were disrupted over the past decade by increased fire emissions that offset the decreases in anthropogenic emissions. Reducing fire risk via effective policies besides mitigation of climate warming, such as wildfire prevention and management, forest restoration, and new revenue generation, could substantially improve air quality and public health in the coming decades.

Tropospheric composition

One of the key products of the Korean Geostationary Environment Monitoring Spectrometer (GEMS) is the NO_2 column which is measured throughout the day over the swath of the instrument in Asia. Validation of the NO_2 columns derived from GEMS measurements are essential because of the novelty of detection throughout the day as opposed to at a single time as with instruments on polar orbiting satellites in sun-synchronous orbits. Ground-based Pandora sensors, operated jointly by NASA, ESA, the US EPA and the Korean National Institute of Environmental Research (NIER) provide high-quality reference measurements to compare with the first retrievals of NO_2 column abundance produced by the GEMS team. Kim et al. (2023) quantify the performance of the GEMS retrievals and illustrate the value of the ground-based validation with international support. The paper also provides a basis for future validation studies for the NASA TEMPO and the ESA Sentinel-4 geostationary satellites.

The hydroxyl radical (OH) fuels atmospheric chemical cycling as the main sink for methane and a driver of the formation and loss of many air pollutants, but direct OH observations are sparse. *Baublitz et al.* (2023) develop and evaluate an observation-based proxy for short-term, spatial variations in OH (ProxyOH) in the remote marine troposphere using comprehensive measurements from the NASA Atmospheric Tomography (ATom) airborne campaign. ProxyOH is a reduced form of the OH steady-state equation representing the dominant OH production and loss pathways in the remote marine troposphere, according to box model simulations of OH constrained with ATom observations. ProxyOH is comprised of only eight variables that are generally observed by routine ground- or satellite-based instruments and scales linearly with *in situ* [OH] spatial variations along the ATom flight tracks. They deconstruct spatial variations in ProxyOH as a first-order approximation of the sensitivity of OH variations to individual terms. Two terms modulate within-region ProxyOH variations—water vapor (H_2O) and, to a lesser extent, nitric oxide (NO). This implies that a limited set of observations could offer an avenue for observation-based mapping of OH spatial variations over much of the remote marine troposphere. Both H_2O and NO are expected to change with climate, while NO also varies strongly with human activities.

Tropospheric ozone variability and trends

Tropospheric ozone is both a pollutant and climate-forcing gas, and positive trends in tropical free-tropospheric (FT) ozone are often linked to emissions growth. *Stauffer et al.* (2024) delve into the less-explored realm of the effects of changing dynamics on tropospheric ozone. Building upon a previous investigation, they re-evaluate ozone trends over equatorial Southeast Asia using 25 years of ozonesonde profile data from the Southern Hemisphere Additional Ozonesondes (SHADOZ) network. The findings reveal large positive ozone trends confined mainly to the early part of the year from February to April. The results suggest that decreasing convective intensity and frequency play a crucial role in the positive trends and buildup of FT ozone over this region, which suppresses the typical lofting and dilution processes. The results highlight the importance of considering monthly or seasonally resolved trends for a comprehensive understanding of ozone dynamics, challenging models and satellites to accurately simulate the patterns observed over the past 25 years.

Wildfire smoke emissions, chemistry, transport and air quality impacts

The growing risk of wildfires is a major threat to public health, property and the environment. *Eck et al.* (2023) use long-term aerosol measurements from NASA's AERONET network to understand the smoke emissions, transport patterns, and their impact on local and regional air quality from these fires. The study analyzes data from the number of AERONET stations spread across the United States to understand how the smoke properties (size, amount) change as it is transported from the western to the eastern United States. The most extreme retrieved-size distributions and associated measured AOD spectra were principally observed in long-distance transported smoke plumes at AERONET sites in Colorado, Maryland, and Virginia, possibly due to further aging during transport. Additionally, strong absorption (darker smoke) was sometimes observed at short wavelengths compared to red wavelength in some plumes, consistent with significant brown carbon and/or coated black carbon absorption in smoke particles. These findings highlight the significant impact that wildfires can have on air quality, both locally and regionally, and how AERONET measurements provide unique value to our scientific understanding.

Heterogeneous chemical cycles of pyrogenic nitrogen and halides influence tropospheric ozone and affect the stratosphere during extreme pyrocumulonimbus (pyroCb) events. *Decker et al.* (2024) report field-derived N_2O_5 uptake coefficients, $\gamma(N_2O_5)$, and $ClNO_2$ yields, $\varphi(ClNO_2)$, from two aircraft campaigns observing fresh smoke in the lower- and mid-troposphere and processed/aged smoke in the upper troposphere and lower stratosphere (UTLS). Derived φ(ClNO2) varied across the full 0–1 range but was typically <0.5 and smallest in a pyroCb (<0.05). Derived $\gamma(N_2O_5)$ was low in agricultural smoke ($0.2–3.6 \times 10^{-3}$), extremely low in mid-tropospheric wildfire smoke (0.1×10^{-3}), but larger in pyroCb-processed smoke ($0.7–5.0 \times 10^{-3}$). Aged biomass burning aerosol in the UTLS had a higher $\gamma(N_2O_5)$ of 17×10^{-3} that increased with sulfate and liquid water, but was still 1–2 orders of magnitude lower than values for aqueous sulfuric aerosol used in stratospheric models.

Disparities in health effects of air pollution

In the United States, studies on nitrogen dioxide (NO_2) trends and pollution-attributable health effects have historically used measurements from *in situ* monitors, which have limited geographical coverage and leave 66% of urban areas unmonitored. Novel tools, including remotely sensed NO_2 measurements and estimates of NO_2 from land-use regression and photochemical models can aid in assessing NO_2 exposure gradients, leveraging their complete spatial coverage. Using these data sets, *Kerr et al.* (2023) find that Black, Hispanic, Asian, and multiracial populations experience NO_2 levels 15–50% higher than the national average in 2019, whereas the non-Hispanic White population is consistently exposed to levels that are 5–15% lower than the national average. By contrast, the *in situ* monitoring network indicates more moderate ethnoracial NO_2 disparities and different rankings of the least- to most-exposed ethnoracial population subgroup. Validating these spatially complete data sets against *in situ* observations reveals similar performance, indicating that all these data sets can be used to understand spatial variations in NO_2. Integrating *in situ* monitoring, satellite data, statistical models, and photochemical models can provide a semi-observational record, complete geospatial coverage, and increasingly high spatial resolution, enhancing future efforts to characterize, map, and track exposure and inequality for highly spatially heterogeneous pollutants like NO_2.

Validation of satellite measurements of tropospheric trace species

Wells et al. (2024) use NDACC FTIR data to validate CrIS measurements of the VOCs methanol, ethane, ethyne and hydrogen cyanide. This work is significant because as satellite programs focus more on tropospheric species, air quality, tropospheric ozone and ozone precurors, these orbital sensors need to be validated. Most sensors however are not sensitive to the surface values due to boundary layer dynamics and mixing variability. The NDACC FTIR comprise the only network of consistent data that are available that have that sensitivity. The validation effort here relies solely on NDACC data and is the first validation for ethyne. We expect this to continue and broaden to other species in the future and the NDACC to become increasingly important for these validation studies.

Greenhouse gases, the carbon cycle and climate change

ACFA supports research into the emissions and fluxes of the greenhouse CO_2, methane (CH_4) and nitrous oxide (N_2O). These involve data from the two NASA Orbiting Climate Observatories, OCO-2 and OCO-3 and from the ground-based Total Carbon Column Observing Network (TCCON). These observations also underpin observations and modeling of the carbon cycle by NASA-supported researchers under the Carbon Monitoring System (CMS). Eight papers are highlighted here.

CO_2 fluxes and carbon uptake and exchanges

J. Liu et al. (2024) study the 2021 La Niña and investigate mechanisms behind the near-neutral impact of the 2021 La Niña on the atmospheric CO_2 growth rate. This is in contrast with the fact that La Niña climate anomalies have historically been associated with substantial reductions in the atmospheric CO_2. Using an ensemble of net CO_2 fluxes constrained by XCO2 observations from OCO-2 observations and estimates of gross primary production and fire carbon emissions, they show that the near-neutral atmospheric CO_2 growth rate in 2021 was the result of a compensation between increased net carbon uptake over the tropics and reduced net carbon uptake over the Northern Hemisphere mid-latitudes. Specifically, extreme drought and warm anomalies in Europe and Asia reduced the net carbon uptake and offset 72% of the increased net carbon uptake over the tropics in 2021. As the frequency of extreme La Niña events are expected to become more frequent in the future, this study demonstrates that regional processes can shape the trajectory of atmospheric CO_2 concentrations. It also underscores the critical importance for continually monitoring the natural carbon cycle at regional scales to inform and support effective carbon-climate policies.

Parazoo et al. (2024) use NASA models and satellite observations to determine (a) the impact of flash drought on carbon exchange in land ecosystems, and (b) the extent to which satellite remote sensing can improve flash drought early warning. Flash droughts — the rapid drying of land and intensification of drought conditions — have devasting impacts to natural resources, food supplies, and the economy but are notoriously difficult to predict. Using carbon and water cycle data from NASA OCO-2 and Soil Moisture Active and Passive missions, their study shows that solar-induced chlorophyll fluorescence (SIF) from OCO-2 can serve as an early warning indicator for flash drought events at lead times of 6–12 weeks across diverse landscapes and ecoregions in North America. They also show that beneficial environmental conditions occurring prior to onset of flash drought led to an increase in carbon uptake in ecosystems, which is then fully offset by carbon loss during and post-drought. While terrestrial carbon models struggle to capture this dual, competing response, spaceborne SIF can be a valuable tool for tracking the cascade of events around flash droughts.

The BlueFlux field campaign, supported by NASA's Carbon Monitoring System, will develop prototype blue carbon products to inform coastal carbon management. While blue carbon has been suggested as a nature-based climate solution (NBS) to remove carbon dioxide (CO_2) from the atmosphere, these ecosystems also release additional greenhouse gases (GHGs) such as methane (CH_4) and are sensitive to disturbances including hurricanes and sea-level rise. As reported by *Poulter et al.* (2023), BlueFlux is conducting multi-scale measurements in Southern Florida of CO_2 and CH_4 fluxes across coastal landscapes, combined these with long-term carbon burial using chambers, flux towers, and aircraft combined with remote-sensing observations for regional upscaling. During the first deployment in April 2022, CO_2 uptake and CH_4 emissions across the Everglades National Park averaged −4.9 ± 4.7 μmol CO_2 m^{-2} s^{-1} and 19.8 ± 41.1 nmol CH_4 m^{-2} s^{-1}, respectively. When scaled to the region, mangrove CH_4 emissions offset the mangrove CO_2 uptake by about 5%, leading to total net uptake of 31.8 Tg CO2-eq y^{-1}. Subsequent field campaigns will measure diurnal and seasonal changes in emissions and integrate measurements of long-term carbon burial to develop comprehensive annual and long-term GHG budgets to inform blue carbon as a climate solution.

Monitoring of greenhouse gases

Sulfur hexafluoride (SF_6) is a potent greenhouse gas. *An et al.* (2024) use long-term atmospheric observations in China to determine its SF_6 emissions. They find that Chinese emissions increased substantially from 2.6 (2.3-2.7, 68% uncertainty) Gg yr^{-1} in 2011 to 5.1 (4.8-5.4) Gg yr^{-1} in 2021. This increase from China is larger than the rise in global total emissions estimated from Advanced Global Atmospheric Gases Experiment (AGAGE) measurements, implying that it has offset falling emissions from other countries. Emissions in the western regions of China, which have not been well quantified in previous measurement-based estimates, contribute significantly to the national SF_6 emissions, likely due to substantial power generation and transmission in that area. The CO_2 equivalent emissions of SF_6 in China in 2021 were 125 (117-132) million tonnes (MT), comparable to the national total CO_2 emissions of countries such as the Netherlands. These increasing SF_6 emissions offset some of the CO_2 reductions achieved through transitioning to renewable energy in the power industry.

The Montreal Protocol and its Amendments regulate the production and consumption of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). While the hydrofluorocarbons (HFCs) have been developed as substitutes to the CFC products, they are now also controlled under the Kigali Amendment (2016). *Pardo Cantos et al.* (2024) discuss the first attempt at retrieving HFCs with ground-based Fourier Transform InfraRed (FTIR) observations at Jungfraujoch, a station in the Network for the Detection of Atmospheric Composition Change (NDACC). They find the FTIR HFC data to be in good agreement with (a) simulations of the TOMCAT 3-D chemical transport model, (b) Atmospheric Chemistry Experiment (ACE-FTS) L2 v5.2 retrievals, and (c) the Jungfraujoch *in situ* surface observations. Overall trends of HFC-134a for the period 2004–2022 are 7.34 ± 0.16% yr^{-1}, 7.29 ± 0.16 % yr^{-1}, 6.61 ± 0.05 % yr^{-1} for FTIR, ACE-FTS and *in situ* observations, respectively, and the TOMCAT trend was 7.12 ± 0.05 % yr^{-1}. The success of this monitoring strategy suggests that it could be implemented at other NDACC sites to achieve a quasi-global detection of this species using the FTIR remote sensing technique.

Methane emissions

With airborne methane surveys of oil and gas systems continuing to discover large emissions missing from official estimates, the true scope of methane emissions from energy production has yet to be quantified. *Sherwin et al.* (2024) integrate approximately one million aerial site measurements into regional emissions inventories for six regions in the

USA, comprising 52% of onshore oil and 29% of gas production over 15 aerial campaigns. Total estimated emissions range from less than 1 % of covered natural gas production in a high-productivity, gas-rich region to 9.63% in a rapidly expanding, oil-focused region. The six-region weighted average is 2.95% – roughly three times the national government inventory estimate. Less than 2% of of well sites contribute the majority (50–79%) of well-site emissions in 11 out of 15 surveys. Ancillary midstream facilities, including pipelines, contribute 18–57% of estimated regional emissions, similarly concentrated in a small number of point sources. Together, the emissions quantified here represent an annual loss of roughly US$1 billion in commercial gas value and a US$9.3 billion annual social cost. Repeated, comprehensive, regional remote-sensing surveys offer a path to detect these low-frequency, high-consequence emissions for rapid mitigation, incorporation into official emissions inventories and assessment of the most effective emission-finding technologies for a given region.

Methane, a powerful greenhouse gas, has a short atmospheric lifetime (~12 years), so that methane emissions reductions will have a rapid impact on climate forcing. In megacities such as Los Angeles (LA), natural gas leakage is the primary atmospheric methane source. The magnitudes and trends of fugitive emissions of natural gas are largely unknown and need to be quantified to verify compliance with emission reduction targets. *Zeng et al.* (2024) use atmospheric remote sensing data to show that, in contrast to the observed global increase in methane emissions, LA-area emissions decreased during 2011-2020 at a mean rate of $-1.57 \pm 0.41\%$ yr^{-1}. However, the natural gas utility calculations indicate a much larger negative emissions trend of −5.8 %/yr. The large difference between top-down and bottom-up trends reflects the uncertainties in estimating the achieved emissions reductions. Actions taken in LA can be a blueprint for COP28 and future efforts to reduce methane emissions.

The Total Carbon Column Observing Network (TCCON) is a key source of validation for space-based greenhouse gas (GHG) measurements and is an essential transfer standard to tie such measurements to the same measurement scales as *in situ* data. It is also a valuable source of data to constrain carbon cycle fluxes and anthropogenic emission due to its long data record and ability to measure the variation of total columns throughout the day. *Laughner et al. (2024)* describe the updates implemented in the GGG2020 retrieval used by the TCCON sites to produce their Level 2 data. Key updates include changes to the interferogram to spectrum conversion, improved *a priori* meteorology and trace gas profiles, updated spectroscopy to eliminate spurious dependencies, more flexible continuum fitting, a correction for remaining airmass dependence better suited to the full network, and more consistent averaging of column amounts retrieved for the same gas in different frequency windows. The method used to tie TCCON data to the World Meteorological Organization (WMO) scales for GHG measurements is also documented in detail, supporting the metrological connection between *in situ* and remotely sensed GHG data.

Stratospheric composition change & ozone depletion.

The ACFA Upper Atmosphere Research Program (UARP) and its associated space-borne missions, airborne campaigns and ground-based observational networks support the international effort to understand the recovery of ozone and the concomitant impacts of a changing stratospheric composition. We highlight in this section twenty papers covering a range of the topics including the recovery from stratospheric ozone depletion and associated trends, the effects of the 2022 eruption of the Hunga volcano, and the effects of smoke in the stratosphere from pyrocumulonimbus.

Stratospheric ozone depletion, recovery and trends

Herman et al. (2023) examine monthly-averaged total column ozone data from the NASA Merged Ozone Data Set (MOD) to show that the latitude-dependent ozone depletion turnaround dates TA(θ) - the approximate date when the zonally averaged ozone ceased decreasing - range from 1994 to 1998. The newly calculated systematic latitude-dependent and hemispherically asymmetric shape of the turnaround dates currently does not appear in the suite of chemistry–climate models that are part of the Chemistry–Climate Model Validation Activity (CCMVal), which combines the effects of photochemistry, volcanic eruptions, and dynamics in its estimate of ozone recovery. Trends of zonally averaged total column ozone in percent per decade were computed before and after TA(θ) using two different trend estimate methods that closely agree, (a) Fourier series multivariate linear regression and (b) linear regression on annual averages. During the period 1979 to TA(θ), the most dramatic rates of Southern Hemisphere ozone loss were -10.9± 3% per decade at 77.5°S and −8.0 ± 1.1% per decade at 65° S. These are about double the Northern Hemisphere loss rates for the corresponding latitude bands. Post turnaround, there was an increase at 65° S of 1.6±1.4% per decade with smaller increases from 55 to 25° S and a small decrease at 35°N of −0.4±0.3 % per decade. Based on this analysis, there only has been a small recovery in the SH toward 1979 ozone values and almost none in the NH except for the Antarctic region.

Stratospheric ozone within the Southern Hemisphere springtime polar vortex has been a subject of intensive research since the discovery of the Antarctic ozone hole. *Fioletov et al.* (2023) used available records of focused Moon (FM) observations by Dobson and Brewer spectrophotometers at the Amundsen–Scott South Pole Station (for the periods 1964–2022 and 2008–2022, respectively) as well as integrated ozonesonde profiles (1986–2022) and MERRA-2 reanalysis data (1980–2022) to estimate the total ozone variability and long-term changes over the South Pole. While total ozone records in the Antractic polar spring are often used to detect ozone recovery, the wintertime ozone in the vortex is less studied. The recent wintertime ozone values over the South Pole were about 12 % below the pre-1980s level; *i.e.,* the decline there was nearly twice as large as that over southern midlatitudes. Thus, wintertime ozone there can be used as an indicator of the state of the ozone layer.

Pazmiño et al. (2023) evaluate the vortex-averaged ozone loss over the last 3 decades for both polar regions using a passive ozone tracer in the TOMCAT/SLIMCAT chemical transport model and total ozone observations from Systeme d'Analyse par Observation Zenithale (SAOZ) ground-based instruments and Multi-Sensor Reanalysis (MSR2). They assess the ozone recovery rate over both polar regions based upon (a) the maximum ozone loss at the end of the winter, (b) the onset day of ozone loss at a specific threshold, and (c) the ozone loss residuals computed from the differences between annual ozone loss and ozone loss values regressed with respect to sunlit volume of polar stratospheric clouds (VPSCs). The Arctic exhibits large interannual variability in (a), and no significant trend is detected; this result is highly influenced by the record ozone losses in 2011 and 2020. There is a negative trend in Arctic ozone loss residuals (c) though with limited significance at the 2 sigma level. These point to a potential quantitative detection of ozone recovery in the Arctic springtime lower stratosphere.

Stratospheric ozone depletion from halocarbons is partly countered by pollution-driven increases in tropospheric ozone, with transport connecting the two. While recognizing this connection, the quadrennial WMO Ozone Assessments' evaluations of observations and processes often split the chapters at the tropopause boundary. Using a chemistry-transport model *Prather* (2024) finds that air-pollution ozone enhancements in the troposphere spill over into the stratosphere at significant rates, that is, 13%–34% of the excess tropospheric burden appears in the lowermost extra-tropical stratosphere. As we track the anticipated recovery of the observed ozone depletion, it should recognized that as much 20% of that recovery may come from the transport of increasing tropospheric ozone into the stratosphere.

The Montreal Protocol and its Amendments have been successful using production/consumption controls in curbing emissions of ozone-depleting substances (expressed by their equivalent effective chlorine, EEC) and potent greenhouse gases (expressed by their direct radiative forcing, DRF). Using hydrochlorofluorocarbon (HCFC; mainly HCFC-22, -141b and -142b) measurements from the Advanced Global Atmospheric Gases Experiment (AGAGE) and the National Atmospheric and Oceanic Administration (NOAA), *Western et al.* (2024) find that the global DRF from HCFCs peaked in 2021 at 61.75 ± 0.056 mWm^{-2}, and the EEC also peaked in 2021 at 321.69 ± 0.27 ppt. By 2023, these values had already dropped to 61.28 ± 0.07 mW m^{-2} and 319.33 ± 0.33 ppt respectively. These decreases have begun 5 years before the most recent projected decreases. This important milestone demonstrates the benefits of the Montreal Protocol for mitigating both climate change and stratospheric ozone layer loss.

The Montreal Protocol has phased down the consumption and production of a large number of halogenated compounds such as CFCs, due to their potential for depleting stratospheric ozone. However, the consumption and production of a class of halogenated compounds, referred to as very short-lived substances (VSLS), is not controlled by the Montreal Protocol. Evidence is growing that globally increasing emissions of human-produced chlorinated VSLS (Cl-VSLS) could have an impact on stratospheric ozone. *Roozitalab et al.* (2024) present comprehensive aircraft measurements coupled to modeling of the major speciated Cl-VSLS that show their present day global distribution at altitudes up to 12 km and also show that Asian emissions are responsible for the majority of observed Cl-VSLS throughout the troposphere including the Southern Hemisphere.

Long-term ground-based ozone measurements are crucial to studying the recovery of stratospheric ozone as well as the trends of tropospheric ozone. *Björklund et al.* (2023)

perform an intercomparison study of total column ozone and multiple partial ozone columns over the period 2000-2022 based on the Fourier transform infrared (FTIR) spectrometer and the Dobson Umkehr, ozonesonde, lidar, and microwave radiometer ground-based measurements available at the Lauder, NZ NDACC site. The FTIR total column ozone comparison shows a bias and strong scatter well within the intrument's combined systematic and random uncertainties respectively, though there is a drift of 0.6 ± 0.5 % per decade if the full time series is considered. In the troposphere they find a low bias of -1.9 % with the ozonesondes. No drift is found among the three instruments in the troposphere. In both the lower and upper stratosphere, all instruments are biased low with respect to FTIR (-1.2 % to -6.8 %), but all are within the range of the systematic uncertainties. In the middle stratosphere there is a negative bias of around -5.2 to -6.6 %, pointing towards too high values for FTIR in this partial column. While they find no significant drift in the stratosphere between ozonesonde and FTIR, there are a number of drifts apparent in other pairings. These suggest that deviations in stratosphere ozone trends derived from different instrumental records cannot be explained by different sampling, vertical sensitivity or time periods and data gaps.

Impacts of the eruption of the Hunga volcano on stratospheric composition

The January 2022 eruption of the submarine Hunga volcano injected an unprecedented amount of water vapor directly into the (normally very dry) stratosphere, almost instantaneously increasing total stratospheric water vapor by about 10%. Although Hunga discharged much less SO_2 into the stratosphere than Mount Pinatubo in 1991, it produced the largest enhancement in stratospheric aerosol loading since then. *Santee et al.* (2023) and *Wilmouth et al.* (2023) analyzed Aura MLS and other satellite measurements and found evidence of widespread chlorine and nitrogen repartitioning in the extrapolar Southern Hemisphere stratosphere in the months following the eruption. Observed composition changes were shown to be consistent with heterogeneous processing on volcanic sulfate aerosol, in particular the hydrolysis of N_2O_5. However, the moderate enhancements in reactive chlorine in the southern mid- and low-latitude stratosphere did not cause appreciable chemical ozone loss.

Schoeberl et al. (2023) examined the aerosol and water vapor anomalies from the eruption of the Hunga volanco that persisted in the Southern Hemisphere throughout 2022. The water vapor anomaly increased the net downward IR radiative flux whereas the aerosol layer reduced the direct solar forcing. As the direct solar flux reduction is larger than the increased IR flux, they predict that the net tropospheric forcing would be negative, with the changes in radiative forcing peaking in July and August and diminishing thereafter. Scaling to the observed cooling after the 1991 Pinatubo eruption, the effect of the Hunga eruption would be to cool the 2022 Southern Hemisphere's average surface temperatures by less than 0.037°C.

The limited impact of the plume on the Antarctic vortex

After the Hunga eruption, there had been speculation that the excess stratospheric moisture would affect the 2022 Antarctic ozone hole. Using MLS measurements, however, *Manney et al.* (2023**)** showed that, although the Hunga plume reached the Southern Hemisphere polar region by June/July 2022, it was then stalled by the very strong barrier to transport at the edge of the Antarctic polar vortex and did not penetrate into the vortex interior to any significant extent. Averages of various chemical species measured by MLS indicated that chemical processing and ozone loss inside the vortex were unexceptional; thus, they found no evidence of a substantial impact from the Hunga hydration on the 2022 Antarctic ozone.

When the Antarctic vortex did break down at the end of the winter, moist air flooded into the southern high latitudes; consequently, it was very humid throughout the region when the 2023 Antarctic polar vortex formed. *Santee et al.* (2024) found that the extraordinary water vapor enhancement from the Hunga eruption prompted unusually early and vertically extensive polar stratospheric cloud activity in the 2023 Antarctic early winter. As a result, heterogeneous chlorine activation occurred weeks earlier and at higher altitudes than typical, and dehydration (via sedimentation of ice clouds) also removed more water vapor from the stratosphere than usual. Nevertheless, cumulative chemical ozone losses at the end of the 2023 Antarctic ozone hole season were unremarkable, because chemical processing ran to completion by mid-winter, as it does every year in the Antarctic. Thus, "saturation" of chemical processing prevented an exceptionally severe ozone hole in 2023.

Ozone depletion associated with the Hunga volcanic plume

The Hunga volcanic eruption of 2022 injected huge amounts of water into the stratosphere and caused a large, rapid loss of ozone. *Evan et al.* (2023) collected *in situ* data on water, aerosols, and ozone in the fresh volcanic plume and combined them with remote sensing observations to show that heterogeneous chlorine activation on humidified volcanic aerosols was the cause of the massive ozone loss that occurred. This loss was primarily triggered by the synergistic effects of strong humidification, radiative cooling, and added aerosol surface area, and this observation supports the suggestion that excess midlatitude stratospheric water associated with convection changes due to global warming could drive increases in lower stratospheric ozone loss.

Near-term in-plume ozone depletion was observed for about 10 days by the Aura Microwave Limb Sounder (MLS) right after the January 2022 eruption of the Hunga volcano. *Zhu et al.* (2023) analyze the dynamic and chemical causes of this ozone depletion. The results show that the eruption's large water injection (~ 150 Tg) from the eruption and ~ 0.0013 Tg injection of ClO, caused ozone loss due to strongly enhanced HO_x and ClO_x cycles and their interactions. Furthermore, the heterogeneous reaction rate for $HOCl + HCl \rightarrow Cl_2 + H_2O$ increased to 104 $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ and was a major cause of chlorine activation, making this event unique compared with springtime polar ozone depletion where $HCl + ClONO_2$ is more important. The large water injection caused relative humidity over ice to increase to 70 %–100 %, decreased the H_2SO_4–H_2O binary solution weight percent to 35 % compared with the 70 % ambient value, and decreased the plume temperature by 2–6 K, both leading to high heterogeneous reaction rates. Plume lofting of ozone-poor air is evident during the first 2 days after the eruption, but ozone concentrations quickly recover because its chemical lifetime is short at 20 *hPa*. The large seawater injection likely lifted ~ 5 Tg Cl into the stratosphere in the form of *NaCl*, but only ~ 0.02 % of that remained as active chlorine in the stratosphere. Lightning NO_x changes are probably not the reason for the initial in-plume O_3 loss.

Hunga volcano aerosols

The Hunga volcano eruptions on January 13 and 15, 2022, produced a plume with the highest signal in stratospheric aerosol optical depth observed since the eruption of Mt. Pinatubo in 1991. *Asher et al.* (2024) flew balloon-borne instruments in a series of launches from Réunion Island and were able to intercept the plume between 7 and 10 days of the eruptions, yielding *in situ* observations of the aerosol number and size distribution and sulfur dioxide (SO_2) and water vapor (H_2O) concentrations. The measurements reveal an unexpected abundance of large particles in the plume, constrain the total sulfur injected to approximately 0.2 Tg, provide information on the altitude of the injection, and indicate that the formation of sulfuric acid aerosol was complete within 3 weeks. Large H_2O enhancements contributed as much as ~30% to ambient aerosol surface area and likely accelerated SO_2 oxidation and aerosol formation rates in the plume to approximately three times faster than under normal stratospheric conditions.

MISR observed the Hunga volcano eruption plume on eight occasions between 15 and 23 January 2022, and *Kahn et al.* (2024) examined used its multi-angle, multi-spectral imagery to retrieve aerosol plume heights along with plume-level motion vectors and to derive radiometric constraints on particle effective size, shape, and light-absorption properties. These retrievals showed the evolving particle properties in two aerosol layers, one near the tropopause and one in the mid-stratosphere. After the initial day (1/15), the retrievals identified only spherical, non-light-absorbing particles, typical of volcanic sulfate/water particles, consistent with model predictions. Particles in the lower-elevation plume observed on 1/15 were larger than all the downwind aerosols and contained significant non-spherical (likely ash) particles. These MISR results are an illustrative example of the contribution that satellite remote-sensing makes toward characterizing volcanic plume evolution.

Duchamp et al. (2023) study the stratospheric aerosol plume produced by the Hunga eruption on 15 January 2022 using the high-quality solar occultation measurements of the SAGE III/ISS instrument. The data reveal that the aerosol sizes are about twice as large as after other documented volcanic eruptions and that the total mass of H_2SO_4 in the liquid droplets of sulfate in the stratosphere was very stable from March 2022 – when it started to be well homogenized in longitude – through to November 2022, when it started to decay. The total mass of 0.66 Tg of H_2SO_4 is in good agreement with early estimates of a stratospheric emission of 0.4–0.5 Tg of SO_2. They suggest that the aerosol radiative impact will not mask the persisting warming effect of the water vapor injected in the stratosphere by the eruption.

Stratospheric influxes of metals vaporized during satellite re-entry

Large increases in the number of low earth orbit satellites are projected in the coming decades. When spent rocket bodies and defunct satellites reenter the atmosphere, they produce metal vapors that condense into aerosol particles that descend into the stratosphere. *Murphy et al.* (2024) show that metals vaporized during spacecraft re-entry appear in stratospheric sulfuric acid particles in ratios consistent with alloys used in spacecraft, with masses of lithium, aluminum, copper, and lead exceeding the cosmic dust influx of those metals. About 10% of stratospheric sulfuric acid particles larger than 120 nm in diameter contain aluminum and other elements from spacecraft reentry. Planned increases in the number of low earth orbit satellites within the next few decades could cause up to half of stratospheric sulfuric acid particles to contain metals from reentry. The influence of this level of metallic content on the properties of stratospheric aerosol is unknown.

Stratosphere-troposphere exchange – Results from ACCLIP and DCOTTS

Deep convection in the Asian summer monsoon is a significant transport process for lifting pollutants from the planetary boundary layer to the tropopause level, enabling efficient injection into the stratosphere of reactive species such as chlorinated very short-lived substances (Cl-VSLSs) that deplete ozone. *Pan et al.* (2024) used airborne observations from the Asian summer monsoon Chemical and Climate Impact Project (ACCLIP) to show that Cl-VSLSs transported to the base of the stratosphere in East Asian summer monsoon convection accounted for ~500 ppt in mean organic chlorine - more than twice that previously reported over the tropical tropopause. With recently observed increases in Cl-VSLS emissions and the ongoing strengthening of the East Asian summer monsoon under global warming, a reevaluation of the contribution of Cl-VSLS injection via the Asian monsoon to the total stratospheric chlorine budget is warranted.

Water vapor's contribution to Earth's radiative forcing is most sensitive to changes in its lower stratosphere concentration. One recognized pathway for rapid increases in stratospheric water vapor is tropopause-overshooting convection. Since this pathway has been rarely sampled, the NASA Dynamics and Chemistry of the Summer Stratosphere (DCOTSS) field project focused on obtaining in situ observations of stratospheric air recently affected by convection over the United States. *Homeyer et al.* (2024) report on the extreme altitudes to which convective hydration was observed. The data show that the overworld stratosphere is routinely hydrated by convection and that past documented records of stratospheric heights of convective hydration were exceeded during several DCOTSS flights. The most extreme event sampled is highlighted, for which stratospheric water vapor was increased by up to 26% at an altitude of 19.25 km, a potential temperature of 463 K, and an ozone mixing ratio >1500 ppbv.

Research aircraft campaigns and ground-based networks supported by ACFA

The Airborne and Satellite Investigation of Air Quality (ASIA-AQ) conducted research flights over four countries (Philippines, South Korea, Thailand, and Taiwan) in February-March 2024. NASA's DC-8 carried an extensive payload to directly sample the regional distribution of pollutants in the lower atmosphere. NASA's G-III carried remote sensors to map key pollutants over metropolitan areas (Manila, Seoul, Bangkok, and Kaohsiung/Tainan). Data collected is undergoing final quality checks. Airborne observations will be combined with ground-based air quality monitoring networks in each country and satellite observations from South Korea's Geostationary Environment Monitoring Spectrometer (GEMS). In collaboration with local environmental agencies and scientists in each country, analysis and early findings regarding emissions sources and factors controlling air quality will be shared with decision makers in early 2025.

The Atmospheric Composition Focus Area provides support to a broad range of ground-based observational networks, both domestic and worldwide. In addition to AGAGE and SHADOZ, these include the Network for Detection of Atmospheric Composition Change (NDACC), the Aerosol Robotics Network (AERONET), the MicroPulse Lidar Network (MPLNet), the Total Carbon Column Observing Network (TCCON), the Pandonia Global Network (PGN), the Tropoospheric Ozone Lidar Network (TOLNet) and the Total Carbon Column Observing Network. The PGN has seen significant growth of ~30 instruments a year and now is comprised of over 165 stations worldwide, with approximately 75 stations in the TEMPO satellite's field of view. TCCON has added three new sites for a total of 26. These networks continue to monitor key atmospheric trace constituents and provide critical validation for satellite-based measurements, despite a few lingering challenges to operations from the COVID pandemic.

<u>Section 1.1.8.2</u> Carbon Cycle and Ecosystems Focus Area

The Carbon Cycle and Ecosystems focus area encompasses research that advances the understanding of the Earth System, including changes in ecosystem structure and function, the critical interconnectivity across human actions and ecosystem health, and the foundational science needed to advance goals and objectives of National Strategies and policy development. The selected research results and other accomplishments highlighted below for the 2024 fiscal year include characterizing rapid ecosystem changes on land and in the ocean and the implications for carbon cycling and ecosystem services, improved understanding of forest degradation and its broader impacts on the Earth system including biodiversity and carbon loss, the impacts of human activities like mining and land change on natural resources and ecosystem health, the role of biodiversity in ecosystem resilience under climate variability, and highlight new technologies which are ushering groundbreaking scientific frontiers and novel applications.

Ocean Biology and Biogeochemistry

Blue carbon ecosystems and nature-based solutions for the climate crisis

In just FY2024, the White House Office of Science and Technology Policy (OSTP) released seven reports and documents, including a number of National Strategies, with visions and actions focused on improved knowledge of ocean resources, the advancement of healthy aquatic ecosystems, environmental justice, and harnessing aquatic ecosystems as nature-based solutions to enable better policy and management decisions that strengthen societies and economies. In particular, blue carbon ecosystems (BCEs) – mangroves, marshes, and seagrasses – and marine carbon dioxide removal (mCDR) have been prominent across all OSTP Strategies as nature-based solutions for the climate crisis, and the foundational research conducted by NASA has advanced the science needed to address goals and objectives of OSTP National Strategies and beyond. For example, Mattson et al. (2024) focused on characterizing multi-decadal wetland losses with Landsat imagery employing a novel spectral mixture analysis method for deconvolving the complex interaction between vegetation and surface water extent. Focusing on the fast-changing Andrade Mesa wetlands along the US-Mexico border, the authors showed that, with the improved technique, the decline in the Mexican wetland over 26 years (1995–2021) was associated with water efficiency measures implemented in the United States, highlighting the hydrological interconnectivity across regions, the delicate interplay between natural ecosystem health and the services they provide, and the impact of human alterations to hydrological resources. The health and productivity of BCEs and their efficiency in carbon uptake and storage are important metrics when quantifying the efficiency of BCEs as natural climate solutions. Salt marshes, in addition to providing protection to infrastructure and coastal communities, have tremendous carbon sequestration potential, but they are difficult to accurately map using earth observations given the complexity of the ecosystems. Hawan and colleagues (2024) focused on characterizing the interannual carbon budgets of tidal marshes in the southeastern US and found that, across years, ecosystem carbon fluxes could vary up to 3-fold, based on the health of the ecosystem. Temperature, precipitation, and river discharge contributed to this variability, and the carbon uptake across the marshes was heterogeneous, suggesting that careful consideration of habitat zones must be taken when computing carbon budgets for these BCEs, and predicting how they will change in the future. In this regard, Cortese et al. (2023) demonstrated that the combination of different types of remote sensing data (e.g. SAR sensors and spectrometers) has great potential to improve mapping of marshes and significantly advance numerical models, critical for evaluating coastal marshes in a changing climate. When it comes to nature-based solutions for climate change, it is critical to be able to quantify the effectiveness of the approach, and the potential ecosystem impacts. This is especially important in a number of mCDR approaches, such as ocean alkalinity enhancements (OAE). Fennel et al. (2023) highlighted the importance of direct observation and skillful, fit-for-purpose models to assess feasibility and effectiveness of the OAE. The authors provided an overview of the most relevant modeling tools, including development needs to make models more applicable to OAE research questions, and the important role of observation assimilation to ensure reliability of the model.

Enhancing the understanding of aquatic biogeochemistry and ecosystem resilience to change

With climate change, aquatic ecosystems and ocean biogeochemistry are changing; understanding how these changes impact ecosystem function is important to predict resilience in a fast-changing planet. Indigenous traditional knowledge (ITK) and community involvement to understand changing ecosystems can improve resilience and mitigate climate-induced impacts. ITK can be particularly powerful when married with modern technology, as demonstrated by Stewart et al. (2024); the authors, with support received as part of the NASA MUREP OCEAN project, report on the success of using Uncrewed Aerial Vehicles (UAVs) for integrated coastal zone management of cultural heritage sites such as Loko iʻa, traditional Hawaiian fishponds that provide sustainable food resources for local communities. The study demonstrated that UAVs are effective tools for monitoring and planning for the future impacts of sea level rise on coastal cultural heritage sites, and how this high-tech information complements traditional practices to thrive in a changing climate. Some of the most rapid ecosystem changes are being observed in polar regions, where warming is occurring at an unprecedented pace. For example, Turner et al. (2024) examined changes in phytoplankton phenology - the timing of annually occurring biological events - in the Antarctic Peninsula and observed that blooms are shifting later in the season over time in ice-associated waters, likely a result of increased wind speeds which provide unfavorable conditions for spring surface phytoplankton accumulation. Later phytoplankton bloom timing over the marginal ice zone and continental shelf can have consequences for surface ocean carbon uptake, food web dynamics, and trophic cascades. Yasunaka et al. (2023) examined changing environmental factors in the Arctic Ocean (AO) induced by the warming of the Arctic, such as biological production, sea ice dynamics, river discharge, and land-ocean carbon fluxes, to evaluate how the AO CO_2 fluxes may be changing, and what this means for local ecosystem and carbon cycling. The work, which covered the period of 1985 to 2018 and contributed to the Regional Carbon Cycle Assessment and Processes phase 2 (RECCAP2) project, found that the AO CO_2 uptake increased over the study period due to the rapid retreat of sea ice. The loss in sea ice cover has enhanced the ocean CO_2 uptake almost as much as the increase in atmospheric CO_2 over the past 34 years. This increase in CO_2 uptake, which impacts the biogeochemistry of Arctic waters including ocean acidification, is expected to affect AO ecosystems and lead to changes in net primary production. In tropical regions, the Great

Atlantic Sargassum Belt (GASB) has been a feature since 2011 and garnered a lot of attention as a staple of changing ocean conditions. However, the sources of nutrients fueling the GASB are not yet clear; Mcgillicuddy and colleagues (2023) attempted to shed some light on the dynamics of the GASB and found that the nutritional status of Sargassum in the GASB is distinct, with higher nitrogen and phosphorus content than populations residing in its Sargasso Sea habitat. Their results suggest that nutrient composition (concentration and isotopic composition) can be used to trace the sources of those nutrients and understand whether they are naturally or anthropogenically driven.

Ushering in a new era of remote sensing for aquatic science and applications

PACE, the Plankton, Aerosol, Cloud, and ocean Ecosystem observatory launched in February 2024, is ushering in a new era of hyperspectral remote sensing with applications far beyond the ocean and atmosphere. While the PACE era is just beginning, results from research using synthetic data are not just promising, but exciting. Cetinić et al. (2024) outlined the potential of hyperspectral data for discriminating phytoplankton community composition, and the importance of understanding its spatial and temporal variability not just to constrain ecosystem health, but also the societal services they provide. Indeed, the hyperspectral nature of PACE opens the possibilities for a number of aquatic applications, including improvements in the detection of marine debris. Castagna et al. (2023) evaluated spectral signatures of diverse pure plastic and non-plastic materials, both in the lab and via airborne measurements, to design, improve, and evaluate detection algorithms, as well as to define optical classes for plastics. The results of the study highlighted the importance of accurate atmospheric correction to reduce errors and suggested that the different plastic-specific algorithms developed can be used as complimentary metrics for plastic remote sensing, potentially enabling plastic optical type classification. They also supported previous observations on the importance of high spatial resolution to minimize mixed spectral signals within a pixel. To this end, Goddijn-Murphy et al. (2024) explored new developments in remote sensing technologies specifically for the detection of marine plastic litter, including lidar and multispectral imaging detection and active reflectance (MiDAR). The authors conclude that there is not one single technique that applies to all kinds of marine litter under different conditions in the aquatic environment, and reinforce the notion of fusing observing approaches to improve detection, in conjunction with validation.

PACE is a trailblazer, and there are other exciting aquatic-focused missions following in its footsteps. Dierssen et al. (2024) described the potential synergies that can result from the novel missions NASA is planning on launching within this decade: The Geostationary Littoral Imaging Radiometer (GLIMR) and the Surface Biology and Geology (SBG) missions. Each monitors unique spatial and temporal scales, enabling unique applications, from inland water quality to mapping of critical submerged aquatic vegetation habitats to better understanding the health of fisheries. These missions, and the synergy across them, will allow us for the first time to monitor the health of aquatic ecosystems in unprecedented ways, and better link processes across the continuum from inland lakes and rivers to the coast and on to the open ocean, assessing how our rapidly changing climate is impacting aquatic ecosystems and their services. But the next decade of aquatic sciences from space is not just hyperspectral: significant advances in lidar technology, focused on the ocean, are on the horizon. These technologies are important because space-based lidar measurements have enabled the observation of global ocean ecosystems in three dimensions. Indeed, as Behrenfeld et al. (2023) note, a new satellite lidar mission with ocean-observing capabilities is being considered in partnership between the Italian Space Agency (ASI) and NASA. This new mission – the Cloud Aerosol Lidar for Global Observations of the Ocean–Land–Atmosphere (CALIGOLA) – would address a number of very important and important science and application questions from the Decadal Survey due to its improved vertical resolution and observation depths (4 optical depths), enabling both daytime and nighttime measurements critical to assess important ecological and ecosystem service questions such as fisheries distribution and polar ecosystem health. In addition, it will extend the climate data record of CALIOP lidar measurements (CALIOP was decommissioned in August 2023). CALIOP, while not designed specifically for ocean use, demonstrated the great potential of lidar ocean retrievals, in particular in high-latitude regions. For example, Zhang et al. (2024) recently exploited the CALIOP data to develop particulate organic and inorganic carbon (POC and PIC, respectively) products, effectively expanding the spatial coverage of the MODIS products to polar regions. Both POC and PIC are a critical component of the carbon cycle and play an important role in the dynamics of marine ecosystems. Lidar retrievals won't just advance our three-dimensional understanding of the ocean; they will support radiometric (passive) ocean color retrievals as well. As Collister and colleagues (2024) demonstrated, lidar measurements of ocean particulate backscatter (b_{bp}) offer independent profiles of atmosphere and ocean optical properties which result in improvements in ocean color retrievals. In addition, ocean lidar retrievals could also provide ocean temperature profiles, important for calculating ocean heat content, as highlighted by Moisan et al., 2024.

Terrestrial Ecology

Impacts of water stress and drought on terrestrial ecosystem health

The changing climate has modified precipitation patterns and water distribution, in many cases exacerbating droughts and reducing water availability. Water stress and drought can have significant impacts on terrestrial ecosystems functions and the carbon cycle, including forest productivity and tropical land carbon uptake. For example, Feldman et al (2024a) examined how soil moisture varied and affected ecosystem water use over the continental US. Using data from NASA's ECOSTRESS (ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station) mission, the researchers analyzed soil moisture profiles at different depths; ECOSTRESS provides high-resolution temperature and evapotranspiration data, allowing for detailed insights into how water availability influences plant water use strategies across various ecosystems. This study highlighted the critical role of soil moisture in maintaining ecosystem health, especially under changing climate conditions; understanding these dynamics can help predict how ecosystems will respond to future droughts and improve water resource management strategies. In another study, Feldman (2024b) evaluated how plants react to shifts in rainfall patterns caused by climate change. Specifically, the authors focused on cases where rainfall events became less frequent but more intense. The research, which integrated evidence from field experiments, satellite data, and models to understand plant responses across different ecosystems, found that plant responses to these altered rainfall patterns are highly variable and depend significantly on the type of ecosystem. In dry ecosystems, plants tend to respond positively to fewer, larger rainfall events due to increased soil moisture availability, while in wet ecosystems, plants often exhibit negative responses due to waterlogging and other stressors. The authors further underscored the critical and unique role satellite data play for observing large-scale patterns and trends that are not easily captured through ground-based methods, enabling researchers to analyze plant responses to changing rainfall patterns across diverse and often remote ecosystems. The criticality of the large-scale, comprehensive, and unique measurements satellites provide was also expressed by Fu et al (2024), who focused on identifying critical soil moisture levels at which plants begin to experience water stress; the study used SMAP and SMOS measurements, which provide high-frequency, global soil moisture data, as well as MODIS which supplies land surface temperature measurements – measurements that are only attainable at regional to global scales via satellites. The authors found that there are significant variations in critical soil moisture levels across different global ecosystems; for instance, dry regions have much lower moisture thresholds for stress compared to humid areas. Over the past 40 years, the frequency of days with soil moisture below the critical threshold has increased, indicating that plants are experiencing more frequent water stress; this has important implications for understanding how ecosystems respond to climate change and for developing strategies to manage ecosystems sustainably. The past four decades, and particularly the last ten years, have also seen an increase in the frequency of flash droughts - rapid drying of land and intensification of drought conditions – which have devastating impacts to vegetation and food security. Flash droughts are difficult to predict and monitor because they are triggered or exacerbated by high temperatures leading to increased evaporative demand, often appearing suddenly and without warning, and can persist weeks to months. Parazoo and colleagues (2024) leverage carbon and water cycle data from NASA OCO-2 and Soil Moisture Active and Passive (SMAP) missions to quantify flash drought impacts on U.S. carbon exchange. The authors found that, on average, carbon uptake and losses balance out over a ±3-month period surrounding flash drought onset, which contrasts with ecosystem models that currently underestimate pre-onset uptake and overestimate post-onset carbon losses. Parazoo et al. (2024) further noted that spaceborne observations of solar induced fluorescence (SIF) provide a reliable indicator of flash droughts at lead times of 2–3 months, due to feedbacks between vegetation growth and soil water loss, facilitating flash drought early warning.

Changes in plant productivity and soil conditions are directly related to the ability of the system to sequester or emit carbon; however, characterizing carbon-climate feedbacks remains difficult due to the limited understanding – and at times rapid changes - of the processes linking carbon and nutrients with ecosystems and their health. Levine et al (2024) underscored how water stress significantly limits carbon uptake in tropical regions. The study analyzed vegetation health and productivity across global tropical ecosystems leveraging various satellite measurements, including gravity as a constraint on water storage, and fluorescence from MODIS, to constrain a mechanistic carbon-water cycle model from 2001 to 2018. Results revealed that water availability, rather than temperature or CO_2 levels, is the dominant factor controlling carbon uptake across all tropical ecosystems. This finding emphasizes the need to prioritize water management in tropical conservation strategies; as tropical forests are critical carbon sinks, maintaining their health is essential for mitigating climate change. In a complementary study, Au et al. (2024)

examined how drought impacts forest productivity and the potential for recovery focusing on the legacy effects of the 2012–2015 California drought on forest carbon pools and fluxes. The study employed the CARbon DAta MOdel fraMework (CARDAMOM), which integrates satellite-derived data from sources like Landsat and MODIS with ground-based observations. The authors found that severe drought can lead to a significant reduction in gross primary productivity (GPP), potentially pushing ecosystems to a tipping point where recovery becomes challenging. This research underscores the importance of understanding the thresholds of environmental stress that lead to ecosystem collapse and highlights the need for effective forest management practices to enhance resilience against prolonged droughts. With this in mind, and to inform strategies for carbon management and climate adaptation in various regions, Potter et al. (2024) examined the responses of different North American ecoregions to drought conditions. The study used the CASA (Carnegie-Ames-Stanford Approach) model, which relies on satellite data from the MODIS sensor to estimate net primary production (NPP) across various biomes. The study found that tropical and subtropical forests exhibit the highest NPP, but all biomes, including temperate and boreal forests, are significantly affected by water availability. The authors also highlighted the critical role of continuous satellite observations to capture spatial and temporal variations in vegetation productivity and water stress which provide a comprehensive view of how drought influences carbon dynamics across diverse ecosystems.

Forest Disturbance and Degradation

Natural and anthropogenic disturbances impact terrestrial ecosystems in different ways; understanding the nature and extent of the impacts, which hinges on adequate monitoring, is critical for developing effective conservation strategies. NASA's Global Ecosystem Dynamics Investigation (GEDI) has demonstrated its ability to characterize change in terrestrial ecosystems at different scales and it continues to provide critical new insight that helps further the understanding of forest dynamics. Holcomb et al (2024) leveraged the detailed 3D GEDI data to examine Amazon rainforest structure and biomass variations with the goal of developing an approach that will enable the assessment of carbon losses and structural changes arising from forest disturbance. By using near-coincident GEDI shots—pairs of lidar measurements taken at different times but at nearly the same location—the researchers were able to demonstrate that their Amazon-wide GEDI dataset was able to measure small disturbances (as small as 30m x 30m), and that even these small perturbations can lead to significant biomass and canopy height losses. They found that tropical forests continue to lose biomass long after the initial disturbance, suggesting that the impacts of disturbances are both immediate and prolonged. GEDI's unique 3D-view of forest structure also enabled the evaluation of different intensities of fire disturbance, including burned areas where the upper canopy retained most of its height, but the understory suffered substantial foliage losses. Subcanopy tropical fires have historically been difficult to measure through remote sensing datasets, and GEDI data hold promise to evaluate impacts of these fire events which affect habitat and ecosystem biodiversity. Indeed, Guerra-Hernandez et al. (2024) examined the potential of GEDI data before and after wildfires to evaluate biomass losses and the connection between fire severity and GEDI 3D metrics. The authors focused on Portugal and Spain, countries in the Mediterranean Basin where fire-induced changes from wildfires are missing. The authors found that structural metrics from GEDI can be used to improve fire severity estimates used globally and to measure forest recovery between fire seasons. These approaches also capture the increasing impact of fire on forest diversity and associated changes in carbon stocks.

Bourgoin et al., (2024) investigated the broader implications of forest degradation, including selective logging, fires, and edge effects, using a combination of satellite remote sensing data and LiDAR data. The study uses a long time series of data from Landsat satellites for historical deforestation data, combined with GEDI data to provide a comprehensive analysis. The findings showed that degradation significantly reduces forest height and biomass, with effects persisting for decades. For example, selective logging and fires reduced canopy height by 15% and 50%, respectively, with low recovery rates even after 20 years. The study also highlighted the extensive reach of edge effects, which extend up to 1.5 km into the forest from degraded areas. This degradation makes forests more vulnerable to further disturbances, such as climate extremes, thus diminishing their resilience and ecological functions. The researchers argue for more stringent conservation efforts to protect these degraded forests and mitigate further biodiversity and carbon loss. Ultimately, these studies highlight the importance of monitoring forest changes at all levels, and in particular to leverage different types of remote sensing measurements. They further underscore that selective logging, fires, and agricultural expansion not only reduce forest height and biomass but also inhibit the forest's ability to recover, further amplifying carbon emissions and biodiversity loss. These insights are essential for informing policies aimed at reducing emissions from deforestation and forest degradation (REDD+) and for developing more effective conservation strategies to maintain forest ecosystem services and biodiversity.

Land Cover and Land Use Change

Mining Boom Across the Tropics is Degrading Rivers

River mineral mining involves intensive excavation and sediment processing in river corridors, altering river forms and releasing excess sediment downstream. Increased suspended sediment loads can reduce water clarity and cause siltation, which may lead to disease and mortality in fish, poor water quality, and damage to human infrastructure. Dethier et al. (2023), investigated river mining on a global scale, synthesizing its physical footprint and impacts on hydrologic systems. The authors assembled and analyzed a 37-year satellite database from Landsat 5 and 7 via the NASA/United States Geological Survey Landsat program, including the latest Sentinel-2 data and aerial images from public sources, showing pervasive and increasing river mineral mining worldwide. The authors identified 396 mining districts in 49 countries, concentrated in tropical waterways universally altered by mining-derived sediment. Of 173 mining-affected rivers, 80% have suspended sediment concentrations (SSCs) more than double pre-mining levels. In 30 countries where mining affects large (>50 m wide) rivers, the authors reported that roughly 23% of large river lengths are altered by mining-derived sediment. This globe-spanning effect represents 35,000 river kilometers, 6% of all large tropical river reaches. The findings highlight the ubiquity and intensity of mining-associated degradation in tropical river systems.

Mapping natural and social drivers of landscape degradation

Mapping landscape disturbances is crucial for ecosystem monitoring, estimating environmental drivers, and developing strategies to enhance ecosystem resilience. High-resolution commercial satellite data, like PlanetScope multispectral imagery at 3-m resolution and near-daily frequency, offers new capabilities to observe, quantify and characterize landscape changes. Roy et al. (2024) examined the incidence, extent, and characteristics of the 2023 Maui wildfires using multi-resolution global satellite fire products from PlanetScope, MODIS, and VIIRS, and compared the burned area product using a published deep learning algorithm. The authors found that while the MODIS 500 m burned area product was too coarse to map most of the burned areas, the PlanetScope constellation provided the necessary imagery with appropriate spatial and temporal resolution for detailed burned area mapping. In a study by Dixon et al. (2023), canopy-scale (3 × 3-m) tree/shrub mortality and survival from California wildfires were detected using PlanetScope monthly time series and a 3D Spatio-Temporal Convolutional Neural Network (ST-CNN) deep learning model. A large set of labels was collected via a semi-automatic workflow combining pre-disturbance lidar crown segmentation and post-disturbance aerial imagery interpretation. The ST-CNN model showed high tree mortality detection accuracy in the Sierra Nevada and North Coast Mountains (~80%), but a slight decrease in the sparser Central Foothills and South Coast and Mountains (~70%) due to confusion between shrub and tree mortality. The ST-CNN was scalable for regional application on all large 2020 wildfires in California (1.6 Mha burn area), showing an overall 3-m tree mortality rate of 58.8%. These data are expected to improve higher-resolution monitoring and assessment of forest disturbance impacts, enhance the understanding of forest vulnerability, and support forest management strategies. Cortner et al. (2024) explored drivers of forest degradation in Georgia, at the heart of the Caucasus region, where forest degradation has been the largest land change process over the last 30 years. The authors combined land-cover change estimates, Georgian statistical data, and historical institutional change data to examine socioeconomic drivers of forest degradation and found that natural drivers, such as higher winter temperature and drought, were associated with higher degradation at the regional scale, while a mixture of anthropogenic and natural causes, such as major institutional changes and drought, were associated with higher forest degradation at the national level. Their results challenge the narrative that poverty and a lack of alternative energy infrastructure drive forest degradation and suggest that government policies banning household fuelwood cutting, including the new Forest Code of 2020, may not reduce forest degradation. The authors further suggest that improved data on wood harvesting are needed, as well as more research on the commercial drivers of degradation and political shifts, to better inform forest policy in the region, especially given ongoing risks from climate change.

Monitoring changes in Eurasia's land use and change

The Russian-Ukrainian War, ongoing since 2014, impacts an area containing Emerald Network environmental-protection sites created through the implementation of the Bern Convention on the Conservation of European Wildlife and Natural Habitats. Using Landsat 5, 7, 8 and Sentinel-2 data, Shumilo et al., (2023) analyzed tree cover changes in the Luhansk region's Emerald Network protected areas from 1996 to 2020. The results revealed that the implementation of Bern Convention conservation policies led to a shift from deforestation (−4% each) to reforestation (+8% and +10%) on both sides of the

Emerald Network divided by the demarcation line in 2014. They also showed that, despite the war, territories under Ukraine control after 2014 continued reforestation (+9%), while sites under Russian control experienced dramatic forest loss (−25%). These findings emphasize the significant consequences of warfare-induced separation of local institutions on conservation areas and underscore the positive impact of the Emerald Network establishment, both before and after the conflict's onset.

Over the past two decades, Russia has experienced an accelerated anthropogenic land cover and use change due to Russia's policy towards land use. Since the year 2000, Russia has experienced large-scale increases (149%) in wheat production and starting in 2018 accounted for almost 25% of all global wheat exports. This represents a significant land cover and land use change driven primarily by winter wheat growth. Abys et al. (2024), utilizing MODIS data, mapped over the period 2001 and 2020, annual winter crop in southwestern Russia and found that 40% of southwestern Russia experienced changes in land cover and land use including a 29% growth in winter wheat cropland. Of this growth, 66% is attributed to winter wheat cropland expansion (planting in new areas) and 34% to intensification (increased planting rate). The observed growth in winter cropland was latitudinally dichotomous where northernmost regions experienced areal expansion and southernmost regions intensification. The authors conclude that there remains significant capacity for winter crop intensification, and underscore that understanding this growth and the future of this domestic industry is important to predict potential impacts to the world wheat market stability and food security as well as environmental consequences of such growth.

Biodiversity and Ecological Conservation

Anthropogenic mortality and impacts on ecosystems resilience and distribution

Human activities profoundly impact animal populations through both static and dynamic interactions. Roads, buildings, and night-time artificial lights pose significant threats to wildlife, contributing to direct mortality and long-term population declines. Farnsworth et al. (2024) highlighted the issue of bird mortality, pointing out that some 388–965 million birds die annually in the United States in building collisions due to disorientation induced by light. The authors argue for improved bird-safe solutions, laws and enforcement to reduce building strikes, and reinforcing educational efforts and voluntary compliance to reduce bird mortality, which are the proverbial canary in the coal mine and help indicate the nation's environmental health. Bardavid et al. (2024) focused on understanding the sensitivity or tolerance of medium- and large-sized mammal species (e.g. tapir, deer, etc.) in the Southern Yungas of Argentina to human pressure combining camera traps, NASA satellite remote sensing, and socioeconomic data from NASA's Socioeconomic Data and Applications Center (SEDAC). The authors discovered that species exhibit varying responses to the human footprint index they defined. By understanding the likelihood of habitat use in relation to each species' sensitivity, more effective mitigation strategies can be implemented proactively, reducing the risk of severe impacts on wildlife. Keany et al. (2024) focused on understanding the ecological role of African forest elephants, a critically endangered species due to poaching, across the Afrotropical region. While their role as seed dispersers is well known, it is less clear to what extent African forest elephants, through the creation of elephant trails and browsing the understory, drive large-scale processes that determine forest structure. The authors leveraged multiple scales of lidar data collected by NASA in Lopé National Park, Gabon from 2015 to 2022 and found that they indeed modify habitats through trail creation and browsing, influencing forest structure and promoting carbon-dense tree growth. The study underscored their role as ecosystem engineers, shaping forest canopies through their browsing habits. Recent technological advancements, like GPS-enabled geolocation tags, have revolutionized animal tracking which provides detailed insights into species biology and habitat quality, and help inform better conservation strategies to reduce anthropogenic impacts on wildlife populations. For instance, Ellis-Soto et al. (2023) discuss the scientific benefits of animal-borne sensors, which can deliver spatially and temporally fine-grain, biological measurements that support ecological assessments and forecasting. They also highlight how the unique information gained from animal-borne sensors, coupled with space-based remote sensing, can offer a precise understanding of ecosystem dynamics and global biodiversity changes at unprecedented and ecologically relevant scales.

Species distribution and ecosystem and biodiversity responses to climate warming
It is increasingly well-documented that climate change drives shifts in biodiversity, such as changes in species' ranges. These shifts in distribution occur as species adapt to altered environmental conditions in an effort to maintain their climatic niche. In mountain ecosystems, such as the Sierra Nevada, the endangered bighorn sheep are adapting their movements to altering snowpack, snowmelt timing, and vegetation phenology. John et al. (2024) investigated the changes in seasonal migration patterns of the Sierra Nevada bighorn sheep over a 20-year period (2003–2022). They found that their vertical movements (increase in elevation) are influenced by climatic factors such as temperature and precipitation. Additionally, the sheep are driven by the search for foraging opportunities tied to the phenological changes in the landscape. These results suggest that Sierra bighorn sheep may be disproportionately affected by future warming and increased storm frequency or intensity, as their vertical movements also serve as a refuge from predators. With heightened predation risks at lower elevations, there could be growing mismatches between the timing of lambing and the availability of high-quality forage, potentially leading to adverse long-term population outcomes.

It has also been documented how biodiversity can stabilize ecological communities through biological redundancy, and how climate and other environmental changes may lead to ecosystem destabilization due to biodiversity loss. Liang et al. (2024) analyzed two decades of kelp forest biodiversity data as it related to the marine heatwave (MHW) in 2014-2016, the most severe MHW ever documented in the North Pacific Ocean. The authors found a very complex picture and distinct responses in heatwave-associated changes based on functional groups likely related to variations in life-history traits and their adaptability to thermal stress. The results suggest that biodiversity indeed plays a key role in stabilizing marine ecosystems, but the resilience of relationships within ecosystems to adverse climate impacts depends on the functional identities of ecological communities. Gholizadeh et al. (2024) used imaging spectroscopy and in-situ observations in managed grasslands to explore the relationship between plant diversity and biological invasions. They found a positive, non-linear association between functional diversity and invasion by *Lespedeza cuneata*, an invasive legume in the U.S. Great Plains. While taxonomic diversity metrics were largely unaffected by *L. cuneata* invasion, importantly, remote sensing revealed significant impacts on functional diversity, varying with invasion intensity and time since fire. The study demonstrated how imaging spectroscopy can provide new insights into biodiversity dynamics at large spatial scales and enhance the ability to manage ecosystems in the face of biological invasions.

Floating marine debris has been a reported mode of marine species dispersal since the nineteenth century. Marine debris, including plastic garbage, acts as a mobile habitat that facilitates species dispersal across the ocean, though little remains known about how biota engage with, and are transported by, debris. Benadon et al. (2023) reviewed 1500 underwater photos from cruises across the Western Pacific and North Pacific Garbage Patch to characterize debris-associated communities and better understand the role of this debris in the transfer of fishes to new geographic regions. The authors identified 13 marine species on debris items, indicating the suitability of these floating plastic habitats for dispersal and migration of these species, and the potential of expanding the range of certain species to new ocean regions. This plastic-associated dispersal mechanism can have impacts on global fish biogeography, potentially altering oceanic communities and inducing shifts in species at broad spatial scales. Pelagic Sargassum is another type of floating (natural) habitat that serves as an important nursery for various marine species. However, its abundance has significantly increased over the last decade, posing threats to native ecosystems and coastal communities. The excessive and unchecked growth of this macroalgae can disrupt local marine environments and lead to negative ecological and economic impacts. The Great Atlantic Sargassum Belt is large enough to be tracked with satellite remote sensing, but its origins and transport pathways remain poorly understood. Zhang et al. (2024), using satellite data from 2000 to 2023, demonstrated that Sargassum in the Gulf of Mexico (GoM) can originate from two primary sources: the northwestern GoM and from physical transport from the northwestern Caribbean Sea. The authors also found that each source has a unique transport route; Sargassum from the northwestern GoM is carried to the eastern GoM by ocean currents and eddies, eventually reaching the Sargasso Sea. In contrast, Sargassum entering the GoM from the northwestern Caribbean Sea moves northward and eastward via the Loop Current System (LCS), and westward across the Campeche Bank through wind-driven currents, influenced by eddies in the northern and central GoM. Overall, the distribution of pelagic Sargassum in the GoM is largely determined by the LCS and associated eddies.

Wildland Fires

Coordinated action is essential for addressing wildland fire management challenges. It also is critical to understand and manage wildfires across their entire lifecycle, which includes the pre-fire, active fire, and post- fire environments. Improved understanding of these environments can lead to enhanced wildfire management, including pre-fire risk reduction, efficient active fire suppression, and effective post-fire hazard mitigation, ultimately reducing negative ecosystem impacts and damage to property and people. The FireSense project is a cross-cutting Earth Science Division effort that is developing and delivering technology and tools to support wildland fire management before, during, and after wildland fires. FireSense employs airborne demonstration campaigns, in close partnership with forest management practitioners, to evaluate capabilities and technologies that support decision making in wildland fire management.

The FireSense project collected airborne measurements at nine locations across four states in the western U.S during the fall of 2023. FireSense, in coordination with its partners, collected information over prescribed burns which enabled researchers and practitioners (i.e., firefighters) to parameterize and calibrate models to more accurately predict fire behavior and smoke production in advance, and to understand how and when to apply data during a wildfire.
Airborne measurements collected data on vegetation and soil moisture, as well as vegetation structure and composition which was validated against simultaneous vegetation and soil moisture sampling on the ground. Data on pre-fire fuel conditions provided scientists with a baseline to compare against for measurements during and after the fire. Active fire observations, using thermal and imaging spectroscopy to cut through smoke, measured fire radiative power, a phrase referring to the energy a fire produces. Understanding the radiative power of a fire enables researchers to analyze the temperature and duration of the blaze, which also impact how high into the atmosphere the smoke plume from the fire will travel. This information is critical for decision makers on the ground as they make real-time calls about how to inform and protect affected communities, deploy firefighting personnel and technology, and calculate long-term effects. Post-fire measurements focused on burn sites to analyze post-fuel consumption and burn severity. This information is then input into models, which compile additional data such as wind patterns, fuel moisture, fuel consumption, land cover type, fire radiative power, and burn duration to lend greater insight into fire behavior and effects. This multi-sensor approach was particularly useful to underscore the strengths of each technique; InSAR was found to be an effective technique for acquiring fire-synchronous estimates of burned area and can complement existing techniques while providing beneficial insensitivities to atmospheric obscurations. These data are also important for comparison and validation of satellite measurements. For example, Michaelides et al. (2024) introduced a new algorithm that uses information from Sentinel-1 InSAR observations to generate burned area-change estimates; in contrast to optical and multispectral instruments, SAR instruments have the ability to operate during day or night conditions, all-weather conditions, and are insensitive to cloud cover or smoke cover during active burn conditions. The authors tested their algorithm over the 2020 Cameron Peak Fire and successfully discriminated recently burned and actively burning areas within a fire zone from unburned areas at high spatial resolution (~10 s of m). Their results were further compared with data from the National Interagency Fire Center and found to be in excellent agreement.

Airborne and surface-based activities

Airborne and surface based (field) activities have continued steadily after the hiatus caused by the COVID-19 pandemic. Some of the highlights of field work for 2023 are below.

ABoVE

For nearly a decade, NASA's Terrestrial Ecology Program has been conducting the Arctic-Boreal Vulnerability Experiment (ABoVE), a major field campaign in Alaska and western Canada. ABoVE seeks a better understanding of the vulnerability and resilience of ecosystems and society to this changing environment. In the summer of 2024, NASA conducted L-band SAR flights on the Gulfstream III between 15-30 August, repeating lines flown during the 2017, 2018, 2019, and 2022 campaigns to continue the multi-year time series, and enable accurate interferometric differencing and comparisons of interannual variability in permafrost active layer thickness, thermokarst, post-fire permafrost degradation and boreal forest structure. Sites included the Peace-Athabascan Delta, road-accessible sites near Yellowknife and Inuvik, and sites in Alaska and Yukon that are of greatest interest to the SAR Working Group and the SWOT validation team. Of note for these flights is the opportunity to produce before-and-after InSAR observations of areas burned in 2022 and 2023 in both Alaska and Canada. Miller et al (2024) summarized the experimental design of and preliminary results from the over 120,000 square kilometers of airborne SAR measurements in Alaska and northwestern Canada taken by ABoVE during 2017, 2018, 2019, and 2022. Several ABoVE-funded investigators are conducting related groundwork in the ABoVE domain throughout the summer of 2024. The summer of 2024 is the last field season for ABoVE.

BioSCape

The BioSCape airborne campaign, conducted in the fall of 2023, utilized advanced NASA remote sensing technology aboard its Gulfstream V and Gulfstream III aircraft. The aircraft, equipped with the AVIRIS-NG, HyTES, LVIS, and PRISM sensors, mapped and analyzed biodiversity across South Africa's hyper-diverse Greater Cape Floristic Region (GCFR) in concert with a host of in-situ observation efforts. This unprecedented airborne remote sensing data collection, now largely available on the BioSCape data portal, enhances efforts in monitoring and conserving the GCFR's ecological integrity and supports sustainable land management practices. NASA's $13M investment in the three-year BioSCape project achieved significant milestones in FY2024, including often concurrent airborne and in-situ measurements over ~45,000 km^2 and the development of an integrated dataset that is easier for new users to access and utilize (via the public-facing BioSCape data portal at https://www.bioscape.io/data).

FireSense project

In the fall of 2023, the FireSense project completed an airborne campaign where data were collected at nine locations across four states in the western U.S. The campaign was centered around four aircrafts: the NASA AFRC B200, the NASA Langley B200, the NASA C-20, and the Dynamic Aviation B200. Pre-fire flights focused on collecting measurements for vegetation and soil moisture as well as vegetation structure and composition, which was validated against simultaneous vegetation and soil moisture sampling on the ground. The Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR), the Scanning L-band Active/Passive (SLAP) instrument, and the Airborne Visible and InfraRed Imaging Spectrometer 3 (AVIRIS-3) collected data on pre-fire and post-fire fuel conditions. FireSense was able to coordinate sampling flights with US Forest Service ground and airborne sensor teams to gather simultaneous data in both daytime and nighttime operations. Airborne sensor data from UAVSAR and AVIRIS-3 were compared with field samples pre- and post- burn to determine how much fuel was consumed in the fire.

NASA's Carbon Monitoring System

Underlying policy efforts to address global climate change is the scientific need to develop the methods to accurately measure and model carbon stocks and fluxes across the wide range of spatial and temporal scales in the Earth system. Initiated in 2010, the NASA Carbon Monitoring System is one of the most ambitious relevant science initiatives to date, exploiting the satellite remote sensing resources, computational capabilities, scientific knowledge, airborne science capabilities, and end-to-end system expertise that are major strengths of the NASA Earth Science program. In the process, CMS scientists actively engage with stakeholders at the federal, state, and local level, as well as with international partners. Recent (FY24) major successes include the
development of prototype blue carbon products to inform coastal carbon management, and the production of a long-term (2002-2021) dataset of wetland methane (CH_4) emission in the boreal arctic region to inform changes in wetland CH_4 emission as a result of a warming climate. Indeed, Poulter et al. (2023), through the BlueFlux project, characterized CO_2 and methane fluxes in Southern Florida and were able to scale these fluxes to the entire region to better constrain greenhouse gas (GHG) fluxes. These integrated measurements of fluxes, coupled with data on long-term carbon burial, are helping develop comprehensive annual and long-term GHG budgets to inform blue carbon as a climate solution. Yuan et al. (2024), upscaling an unprecedented compilation of eddy covariance and chamber observations of Boreal–Arctic wetland CH_4 emissions, found a robust increasing trend of CH_4 emissions with strong inter-annual variability. The authors noted that high CH_4 emissions can be triggered by abnormally high temperatures over high-emission wetlands. Importantly, however, the observed magnitude and trend of wetland CH_4 emissions in the Boreal–Arctic region are not adequately captured in current-generation models, which may bias the estimates in future wetland CH_4 emission driven by amplified Boreal–Arctic warming and greening. Other noteworthy CMS results include the development of the first AI-enabled forest ecosystem model for carbon monitoring applications (Wang et al., 2023), and mapping of carbon in forest wetland soils (Stewart et al., 2024). CMS also contributed to the Global Carbon Budget (Friedlingstein et al., 2023), and to date, the initiative has engaged with >200 stakeholders, produced 689 publications cited 54,356 times, and 170 data products downloaded >115,000 times.

Section 1.1.8.3 Climate Variability and Change Focus Area

Research supported by NASA's Climate Variability and Change (CVC) focus area increases our knowledge of global climate and sea level on seasonal to multidecadal time scales, by focusing on the individual and interactive climate processes occurring in the ocean, atmosphere, land and ice. Through a wide range of disciplinary and interdisciplinary projects, CVC supports the evaluation and utilization of satellite, aircraft and ground-based observations of the global ocean, sea and land-based ice, land surface and atmosphere, as well as their integration into comprehensive, interactive Earth system models and assimilation systems. These activities can be divided into those focused on characterizing the behavior of the Earth system (performance indicator 1.1.8), and those that focus on enhanced understanding and prediction (performance indicator 1.1.9).

It is useful to break the supported activities into three major programs:

Cryosphere in the Earth Climate System
Oceans in the Earth 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:

Cryosphere in the Earth 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 in the Climate System

Sea ice plays a critical role in the Earth system by both reflecting solar radiation and regulating the transfer of heat and momentum between the atmosphere and ocean. NASA continues to study sea ice and its interactions with other components of the Earth System using a number of space-based measurements. 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.

Arctic sea ice has undergone significant change in areal coverage, thickness, ice type since the 1980s and more recently since the early 2000s, where a “New Arctic” regime now exists. Since the sea ice modulates exchanges of energy from the ocean to the atmosphere, this changing sea ice environment has profound effects on the local climate. The Atmospheric Infrared Sounder (AIRS) onboard NASA's Aqua satellite has been collecting twice daily, global data of the Earth's temperature and humidity for more than 20 years. *Boisvert et al. (2023)* used AIRS temperature and humidity data to investigate relationships between the sea ice, and surface and atmospheric conditions between 2003 and 2022. Strongest correlations occur in the fall when the surface and lower atmosphere are tightly coupled. When comparing the first (2003–2012) and last (2013–2022) decade of the New Arctic, results show that the warming and moistening is slowing as the sea ice regime and sea ice loss has stabilized in 2013–2022. Cooling and drying are occurring in winter in the Barents Sea, as well as other peripheral seas, in the last decade possibly due to a negative feedback loop, where winter sea ice regrowth is occurring at a faster pace. This work highlights the importance of sea ice atmosphere interactions and long-term climate data records, specifically in remote and drastically changing locations.

During the summer, highly reflective snow-covered Arctic sea ice with high albedo decreases due to both the disintegration of the ice cover exposing the low-albedo open ocean and melt ponding on the ice surface. Remote sensing observations offer the potential to expand both the spatial and temporal scales over which summer melt can be studied, and new opportunities to detect and monitor melt ponds across the Arctic are available with the launch of earth-observing satellites with high-resolution capabilities that also provide continuous measurements. *Buckley et al. (2023)* investigated sea ice conditions during the 2020 melt season, when warm air temperature anomalies in spring led to early melt onset, an extended melt season, and the second-lowest September minimum Arctic ice extent observed. They focused on the region of the most persistent ice cover and examine melt pond depth retrieved from Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) using two distinct algorithms in concert with a time series of melt pond fraction and ice concentration derived from Sentinel-2 imagery to obtain insights about the melting ice surface in three dimensions. They found that the melt pond fraction derived from Sentinel-2 in the study region increased rapidly in June, with the mean melt pond fraction peaking on June 24, 2020, followed by a slow decrease by July 3, and remained below 10% for the remainder of the season through September 15. Sea ice concentration was consistently high (95%) at the beginning of the melt season until July 4, and as floes disintegrated, it decreased to a minimum of 70% on 30 July and then became more variable, ranging from 75% to 90% for the remainder of the melt season. Their results demonstrate that by combining high-resolution passive and active remote sensing, there now exists the ability to track evolving melt conditions and observe changes in the sea ice cover throughout the summer season.

Land Ice in the Climate System

Nearly every glacier in Greenland has thinned or retreated over the past few decades leading to glacier acceleration, increased rates of sea-level rise and climate impacts around the globe. To understand how calving-front retreat has affected the ice-mass balance of Greenland, *Greene et al. (2024)* combined more than 200,000 manually derived and AI-derived observations of glacier terminus positions collected from 1985 to 2022 and generate a 120-m-resolution mask defining the ice-sheet extent every month for nearly four decades. They showed that since 1985, the Greenland Ice Sheet (GrIS) has lost an area greater than 5,000 square kilometers, corresponding to more than 1,000 gigatons of ice lost to retreat. Their results indicate that, by neglecting calving-front retreat, current consensus estimates of ice-sheet mass balance have underestimated recent mass loss from Greenland by as much as 20%. The mass loss reported in this study has had minimal direct impact on global sea level, but is sufficient to affect ocean circulation and the distribution of heat energy around the globe. On seasonal timescales, Greenland loses almost 200 square kilometers in area (roughly 60 Gt) of ice to retreat each year from a maximum extent in May to a minimum between September and October. They found that multidecadal retreat is highly correlated with the magnitude of seasonal advance and retreat of each glacier, meaning that terminus-position variability on seasonal timescales can serve as an indicator of glacier sensitivity to longer-term climate change.

The Greenland Ice Sheet is a leading contributor to global sea-level rise because climate warming has enhanced surface meltwater runoff. Melt rates are particularly sensitive to air temperatures due to feedbacks with albedo. The primary melt-albedo feedback, fluctuation of seasonal snowlines, however, is determined not only by melt but also by antecedent snowfall which could delay the onset of dark glacier ice exposure. *Ryan et al. (2023)* investigated the role of snowfall versus air temperatures on ice sheet melt-albedo feedbacks using the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard NASA's Terra satellite and combine it with snowfall and air temperature data from NASA's Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2). They found several lines of evidence that snowline fluctuations are driven primarily by air temperatures and that snowfall is a secondary control. Their findings demonstrated that snowfall is unlikely to reduce future ice sheet melt and that ice sheet meltwater runoff should be accurately predicted by air temperatures. Although given the importance of melt-albedo feedbacks, ice sheet models that parameterize albedo or are coupled with regional climate models are likely to provide the most accurate projections of mass loss.

Ice shelves limit the flux of grounded ice into the ocean by buttressing the discharge of land-based ice upstream. Ice shelf weakening and collapse can lead to decreased buttressing and observations increasingly show that some ice shelves have experienced increased melt and increased calving, with recent hypotheses suggesting that increased melt leads to increased fracturing. However, the specific processes that control this correlation are not yet understood, with mechanisms other than melt affecting fracturing. *Watkins et al. (2024)* used the topography of the ice shelf base from BedMachine Antarctica Version 2 to investigate how basal melting and ice deformation contribute to crevasse and melt channel formation and evolution on the Pine Island Ice Shelf in West Antarctica. They found that high basal melt rates and high first principal strain rates lead to substantial roughening of the ice shelf through a collection of features, including melt channels and crevasses. Critically, melt channels and crevasses are the deepest in all directions at locations where the highest rates of melting and straining occur simultaneously. This suggests that the combination of melt rates and strain rates work in tandem to excavate and seed the deepest melt channels and crevasses on ice shelves. These features then may form lines of weakness that transform into rifts and, ultimately, the detachment boundary for calving events. This implies that melt and fracture play an important role in controlling the dynamics of ice shelves.

The knowledge of rifts and icebergs in Antarctica is imperative for understanding drivers and mechanisms controlling ice-shelf retreat. The description of their 3-D structural features has been challenging before the 2018 launch of the Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2), whose goal is to collect high-resolution elevation measurements using a photon-counting laser altimeter system. The great advancements of deep learning in multi-feature characterization enable the recognition of rifts and icebergs from the Global Geolocated Photon Data (ATL03) product. Considering the insufficient 3-D information on rifts and icebergs at an extended spatiotemporal scale, *Huang et al. (2024)* presented a novel deep learning-based approach to recognize rifts and icebergs from ATL03 data. Considering the importance of these surface objects for understanding calving events and their influences on oceanic circulation and temperature change, this approach aims to bridge the existing data gap regarding the structural details of rifts and icebergs. ATL03 data were converted into three feature spaces, followed by the construction of a scene classification network for scene label prediction. This model builds three deep neural networks (DNNs) to separately encode three feature spaces, simultaneously extracting 3-D and 2-D morphological features and topological features from ATL03 data. The generalization capabilities of their model were demonstrated by its successful application to several Antarctic regions, including the Ross, Thwaites, Filchner–Ronne and Larsen C ice shelves, without region-specific training. They concluded that this model could serve as a versatile tool for the large-scale monitoring of rifts and icebergs using high-resolution altimetric measurements.

Short-term tidal grounding line migration in Antarctica can impact ice dynamics at the ice sheet margins and obscures assessments of long-term grounding line advance or retreat. However, the magnitude of tidally-induced grounding line migration is poorly known, and the spatial pattern and modes of variability are not well characterized. *Freer et al. (2023)* developed and applied a technique using the land ice height product (ATL06) from ICESat-2 repeat-track laser altimetry to locate the inland limit of tidal ice shelf flexure for each sampled tide, enabling the magnitude and temporal variability of tidal GL migration to be resolved. They demonstrated its application at an ice plain north of Bungenstockrücken, in a region of the southern Ronne Ice Shelf subject to large ocean tides. They observed a 1,300 square kilometer area of ephemeral grounding over which the grounding line migrates by up to 15 kilometers between low and high tides, and identify four distinct modes of migration: “linear”, “asymmetric”, “threshold” and “hysteresis”. The short-term movement of the grounding line dominates any long-term migration signal in this location, and the distribution of grounding line positions and modes contains information about spatial variability in the ice-bed interface. They presented the impact of extreme tidal grounding line migration on ice shelf-ocean-subglacial systems 20 in Antarctica and made recommendations for how grounding lines should be more precisely defined and documented in future by the community.

Oceans in the Climate System

The ocean plays a fundamental role in the Earth system. Annually, it absorbs 90% of the Earth's Energy Imbalance, the difference between incoming and outgoing energy. The ocean absorbs and stores atmospheric CO2 for millennia. The continuous exchange of heat, water, moisture, and gasses between the ocean and the atmosphere influence climate and weather patterns by releasing the heat that fuels the overlying atmospheric circulation, releasing aerosols that impact cloud cover, 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 Earth climate system utilizing remote and in situ observations, numerical models, and data assimilating systems. The program supports research that characterizes the ocean's intrinsic variability, its dynamics and thermodynamics, and its interactions within the complex system of ocean-atmosphere-land-solid Earth. Below are the most notable discoveries supported by this program and published in 2023-2024 that advanced our understanding of the ocean's role in the climate system.

Ocean dynamics regulate Earth's heat

Earth warming continues unabated: this year NASA/NOAA reported the highest global surface temperatures recorded since the 1850s, showing an increase in surface temperatures by 1.37°C above the late 19th century for 2023 and continuing a warming trend of ~0.2°C/decade. In addition to the Earth's surface, NASA's Ocean Heat and Earth Energy Imbalance (OHC/EEI) Working Group also reports the hottest subsurface ocean heat content and denoting acceleration in ocean and planetary warming (e.g., *Chen et al. 2024*; *Hakuba et al. 2024*; ECCO). For example, *Hakuba et al. 2024* analyzed 21 datasets to assess the rate of ocean heat uptake from various sources, reporting the spread in rates between 0.40 ± 0.12 and 0.96 ± 0.08 W/m^2, depending on the datasets and mapping methods. Most of the heat is absorbed by the upper 2000-m ocean water column, including tropical Atlantic, the Mediterranean Sea, and the Southern Ocean that have seen the highest ocean heat content since the 1950s (*Chen et al., 2024*).

Once absorbed, the heat is redistributed across the planet by the ocean currents and eddies. In particular, a system of ocean currents that carries warm water north and cold waters south, and commonly referred to as the Atlantic Meridional Overturning Circulation (AMOC), has seen renewed attention in the publications and media this year, hypothesizing a potential shutting down of the AMOC system. In contrast, analysis of direct observations are not showing significant decline in AMOC strength. A study by *Le Bras et al. (2023)* combined a variety of in situ observations (mooring and floats) with satellite altimetry data to estimate the strength of AMOC at 35°N latitude and compare with other estimates of the

AMOC transport at 26°N and 41°N from ECCO. Their results do not show a rapid decrease in AMOC trend during the 20th century, being potentially masked by a strong natural variability in the system.

Another prominent system of the ocean currents that redistributes Earth's heat is the Gulf Stream, driven by the wind and Earth's rotation. *Piecuch & Beal (2023)* used Bayesian analysis to quantify the change in Gulf Stream transport since 1982. They found a measurable decline of the volume transport through the Florida Straits over the past 40 years. The estimated multi-decadal decline is about 1.2 ± 1.0 Sv (1 Sverdrup = 10^6 m/s).

Besides horizontal redistribution of heat by ocean currents, another way that oceans affect the Earth's climate involves the mixing of heat anomalies throughout the water column, which generally slows down the rates of surface warming. There are several ocean processes through which mixing can occur. One of them are internal waves, or waves that occur at various depths within the ocean with surface signatures detectable by the satellite radar altimetry. Recent studies by NASA Ocean Surface Topography Science Team, including *Zhao 2023*, reveal the strengthening of the M2 internal tide by 6% in energy over the past 30 years (1993-2022), which is the strongest tidal component with a period of 12 hours and 25 minutes. The results are consistent with those by *Opel et al (2024)* who show that the barotropic M2 tide has weakened over the past 30 years due to the energy transfer to internal tides and in response to the change in the vertical distribution of ocean density and stratification.

Ocean salinity constraints Earth energy and water cycles

NASA Ocean Salinity Science Team (OSST) designed and completed a process study in the Arctic ocean, called Salinity and Stratification at the Sea Ice Edge (SASSIE), to examine the relationship between ocean salinity, near-surface stratification and ocean heat, and sea ice dynamics. *Drushka et al (2024)* report successful data collection during SASSIE field campaign in 2022, including ocean and meteorological observations near the sea ice edge in the Beaufort Sea, along with all the resulting datasets and accompanying software in accordance with NASA's Open Science paradigm. First analysis of the shipboard measurements from SASSIE by and satellite flux analysis by *Carrig et al (2024)* find that the onset of prolonged Arctic darkness in September is the transition where outgoing longwave radiation surpasses incoming solar radiation with a notable increase in short-duration cold air outbreaks. These outbreaks occur when cold mesoscale surface winds go from cooling landmasses or ice caps to the warmer seas. Turbulent heat losses outpaced longwave emission by more than fivefold, accelerated ocean surface cooling in the subsequent 2 months, and led to the complete freeze-up of the Beaufort-Chukchi seas by late November. This understanding has the potential to improve predictive capabilities of the future Arctic changes.

While the global water cycle has been studied separately from the land perspective and the open ocean perspective, *Fournier et al (2023)* showed that the global coastal zone provides an opportunity to monitor aggregated water cycle variability. Global sea surface salinity variability is concentrated near the coasts and that coastal salinity variations at interannual time scales are highly correlated to El Niño Southern Oscillation (ENSO), with global river discharge being the connecting mechanism. Coastal salinity can thus be used to monitor global water cycle variability at interannual time scales. Global warming is expected to lead to changes in the water cycle and in ENSO's intensity and frequency. The global coastal ocean salinity may be where these changes are most detectable in aggregate.

Atlantic ocean circulation affects rainfall in the U.S Midwest via the Great Plains Low-Level Jet. Carr & Ummenhofer (2023) found that most of the anomalous moisture transported to the Midwest on synoptic timescales (a day to a week) originates from the Atlantic Ocean, transported by a strong Great Plains Low-Level Jet.

One of the most striking features of global sea surface salinity patterns is the contrast between salinity minima in the tropical ocean along the equatorial belt and salinity maximum in the subtropical oceans. Latest study by *Yu 2023* examines the nature and variability of the zonal patterns, showing the interplay between the freshening source due to the rainfall associated with the double Intertropical Convergence Zones, and excessive evaporation in the subtropical high-pressure belts. The two features appear to be phase locked and linked by the Ekman wind currents, with tropical salinity minima leading subtropical maxima by 6 months according to the new analysis by *Yu (2023)*.

Fine-scale ocean features influence fluxes, CO2, and biological productivity

Radar technologies have, until recently, been able to deliver information about ocean dynamics on horizontal scales of order 50 km and longer. However, various exchange processes and fluxes of heat, moisture and carbon are occurring on finer, 1-10 km, scales that have the potential to be resolved by recently-launched (SWOT) and future (ODYSEA) satellite missions. *Fu et al (2024)* describes the first results from SWOT to map surface elevation of water over the ocean and land, including coastal regions. In a related study, *Yu et al. 2024* assess the accuracy of SWOT data in the retrieval of marine gravity and bathymetry, reporting high fidelity and accuracy in SWOT bathymetry even after just 10 repeat cycles of pre-validated SWOT sea surface height data.

The divergence of surface ocean horizontal velocity is of great interest because of its direct relation to the near-surface vertical velocity, that has important implications for air–sea exchanges of CO_2 and other gasses, as well as the supply of nutrients from depth that are critical to biological productivity. The analysis presented by *Chelton (2023)* concludes that useful estimates of surface current divergence can be obtained from a future Doppler radar aboard a satellite mission dubbed ODYSEA that is in the early stages of development by NASA.

Air-sea coupling and fluxes regulate weather and global climate

Atmospheric rivers deliver water evaporated from the tropical oceans to the western side of continents, and are often responsible for major floods and storms in the west coast of North America, northern Europe, and Australia. *Shinoda et al (2023)* studied the air-sea heat fluxes associated with the atmospheric in the South-East Indian Ocean. They found that the warm current along the west coast of Australia leads to a large loss of heat from the ocean to the atmosphere and cooling of the sea water, an effect opposite to that of atmospheric river impinging over the West Coast of North America where there is a cold coastal ocean current. *Hsu et al (2024)* investigated the impact of atmospheric rivers on sea surface temperature (SST) over the North Pacific by analyzing 25 years of ECCO ocean reanalysis. They showed that in some regions ocean dynamics can offset over 100% of the anomalous SST warming from atmospheric forcing. In coastal California, enhanced SST warming is the consequence of a reduction in seawater advection due to anomalous southerly winds. There is a large region where the SST shows a warming response to atmospheric rivers due to the overall reduction in the total clouds and subsequent increase in total incoming shortwave radiation.

Ocean extremes and coastal hazards

Kamp et al (2024) used satellite radar altimetry, tide gauge data, and high-resolution models to investigate the role of the Madden-Julian Oscillation (MJO) in forcing coastal flooding and sea surface high extreme events along the coast of Indonesia. They found that most of the coastal extreme events occur during December-February and March-May, with MJO and wind playing the dominant role in setting the events and their strong seasonal differences.

Another study by *Piecuch & Hamlington (2023)* show the change in water levels across the U.S. coastline. They report that "yesterday's high tide is today's new normal", as water levels along part of the Chesapeake Bay, Gulf Coast, and Puerto Rico regularly exceed official high tide due sea level rise.

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

Earth system model development

Integrated Earth System Modeling within CVC focuses on the development and application of comprehensive Earth system models to address CVC science issues. The effort is guided by 4 basic principles: 1. Focus on Earth System Science, 2. Observation Driven Modeling (that is, modeling that responds to and extracts value from the observations that NASA receives), 3. Utilization of ESMs for characterization, diagnosis, prediction and observing system design, and 4. Provision of societal benefits.

Model development is focused on increasing model comprehensiveness, representativeness, and resolution. For instance, atmospheric models with typical resolution in the tens of kilometers cannot resolve the dynamics of air parcel ascent, which varies on scales ranging from tens to hundreds of meters. Small-scale wind fluctuations are thus typically characterized by a subgrid distribution of vertical wind velocity. Using a novel deep learning technique, this year, Barahona et al. [2024] developed a new parameterization for small-scale wind fluctuations by merging data from global storm-resolving model simulations, high-frequency retrievals of vertical velocities, and climate reanalysis products. The parameterization reproduced the observed statistics of and leveraged learned physical relations from the model simulations to guide extrapolation beyond the observed domain. Incorporating observational data during the training phase was found to be critical. The parameterization can be applied online within large-scale atmospheric models, or offline using output from weather forecasting and reanalysis products.

Increasingly machine learning is being exploited to develop model parameterizations that are fast and effective, in combination with observations that are utilized for training. Yang et al. [2023] used a machine learning model to diagnose Antarctic blowing snow (BLSN) properties from Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), data. The study used a random forest classifier for BLSN identification and a random forest regressor for optical depth and height diagnosis. BLSN properties from Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) were used to train the model. Hourly blowing snow property diagnostics were generated which previously had been constrained by satellite orbital path and coverage. Tests of its performance showed that in 2010, the Antarctic BLSN frequency was much higher over East than West Antarctica. High-frequency months were from April to September, during which BLSN frequency exceeds 20% over East Antarctica. In May the BLSN snow frequency was as high as 37%. Due to the suppression by strong surface-based inversions, larger values of BLSN height and optical depth were limited to the coastal regions, where the strength of surface inversions was weaker. This model could trained with other reanalysis output or be driven by an Earth system model, thereby allowing the model to generate predictions of long-term trends and variability in BLSN as environmental conditions change.

Critical to Earth system model representativeness is a good simulation of atmospheric aerosols. This year, the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model, which controls the sources, sinks, and chemistry of aerosols within the Goddard Earth Observing System (GEOS), underwent a major refactoring and update, including a revision of the emissions datasets and the addition of brown carbon [Collow et al. (2024)]. A 4-year benchmark simulation utilizing the new version of the model code, termed GOCART Second Generation (GOCART-2G) and coupled to the Goddard Earth Observing System (GEOS) model, was evaluated using in situ and spaceborne measurements to develop a baseline and prioritize future development. Compared to MODIS retrievals, the model captures the overall spatial pattern and seasonal cycle of aerosol optical depth, but overestimates aerosol extinction over dusty regions and underestimates aerosol extinction over Northern Hemisphere boreal forests. Analysis also suggests that there is a diurnal component to biases in aerosol optical depth over southern Asia and northern Africa. The results presented highlight priorities for future development with GOCART-2G, including improvements for dust, biomass burning aerosols, and anthropogenic aerosols.

Earth system model utilization

Climate models project a future weakening of the Atlantic meridional overturning circulation (AMOC), but the impacts of this weakening on climate are highly uncertain. A key challenge in quantifying the impact of an AMOC decline is isolating its impact on climate. Orbe et al. [2023] isolated the climate impacts of a weakened AMOC using an ensemble of NASA GISS Model E integrations. In these runs internal variability alone results in a spontaneous bifurcation of the ocean flow, wherein 2 out of 10 ensemble members exhibit an entire AMOC collapse, while the other 8 members recover at various stages despite identical forcing of each ensemble member and with no externally prescribed freshwater perturbation. The AMOC collapse produces an abrupt northward shift and strengthening of the Northern Hemisphere (NH) Hadley cell (HC), intensification of the northern midlatitude eddy-driven jet, and a nonlinear shift in the NH circulation. The study suggests that changes in ocean heat flux convergence due to an AMOC collapse can result in profound changes in the NH circulation and continued efforts to quantify the AMOC response to future climate change are needed.

Atmospheric rivers (ARs), intrusions of warm and moist air, can effectively drive weather extremes over the Arctic and trigger subsequent impact on sea ice and climate. What controls the observed multi-decadal Arctic AR trends remains unclear. Ma et al. [2024] used multiple sources of observations and model experiments to find that contrary to the uniform positive trend in climate simulations, the observed Arctic AR frequency increases by twice as much over the Atlantic sector compared to the Pacific sector in 1981-2021. This discrepancy can be reconciled by the observed positive-to-negative phase shift of Interdecadal Pacific Oscillation (IPO) and the negative-to-positive phase shift of Atlantic Multidecadal Oscillation (AMO), which increase and reduce Arctic ARs over the Atlantic and Pacific sectors, respectively. Removing the influence of the IPO and AMO can reduce the projection uncertainties in near-future Arctic AR trends by about 24%, which is important for constraining projection of Arctic warming and the timing of an ice-free Arctic.

Soil dust aerosol composition in Earth system models (ESMs) is traditionally not differentiated but is considered to be homogeneous. However, Obiso [2024] highlights the importance of accurately representing soil dust aerosol composition in Earth system models (ESMs) due to its significant impact on dust climate effects. This work integrates mineral speciation into the NASA Goddard Institute for Space Studies ModelE2.1 to better calculate the shortwave (SW) direct radiative effect (DRE) based on regional soil mineralogy variations. Two coupling schemes for mineral–radiation interaction were explored: external mixing of three mineral components, and a single internal mixture with regionally and temporally varying iron oxide fractions. Findings indicate that incorporating mineralogy enhances dust scattering and global cooling compared to a uniform composition model. The external mixing scheme changes the SW DRE at the top of the atmosphere (TOA) from −0.25 to -0.30 W/m^2, and the cooling increase is accentuated when the internal mixing scheme is configured. Evaluation against AERONET data shows improved dust single scattering albedo (SSA) representation and reduced low bias, though challenges remain in accurately modeling mineral fractions and spatiotemporal correlations.

Given the focus of the NASA Integrated Earth System Modeling effort on utilization of observations, The Clouds and the Earth's Radiant Energy System (CERES) project has now produced over two decades of observed data on the Earth's Energy Imbalance (EEI) and has revealed substantive trends in both the reflected shortwave and outgoing longwave top-of-atmosphere radiation components. Such results could be used for model evaluation and development. Available climate model simulations suggest that these trends are incompatible with purely internal variability, but that the full magnitude and breakdown of the trends are outside of the model ranges. Schmidt [2023] therefore proposes a new, relatively low-cost model intercomparison, CERESMIP, that would target the CERES period (2000-present), with updated forcings to at least the end of 2021. The key metrics of interest will be the EEI and atmospheric feedbacks, and so the analysis will benefit from output from satellite cloud observation simulators.

Section 1.1.8.4 Earth Surface and Interior Focus Area

Introduction

NASA's Earth Surface and Interior focus area (ESI) continues to advance the understanding of core, mantle, and lithospheric structure and dynamics, and interactions between these processes and Earth's fluid envelopes. Research conducted in the past year has also provided the basic understanding and data products needed to inform the assessment and mitigation of natural hazards, including earthquakes, tsunamis, volcanic eruptions, and landslides. ESI's Space Geodesy Program (SGP) continues to produce observations that refine our knowledge of Earth's shape, rotation, orientation, and gravity, foundational to many Earth missions and georeferenced observations. The ESI strategy is founded on the seven scientific challenges identified in the *Challenges and Opportunities for Research in ESI (CORE) Report* (Davis et al, 2016, http://go.nasa.gov/2hmZLQO): 1. [Plate boundaries], 2. [Tectonics and surface processes], 3. [Solid Earth and sea level], 4. [Magmatic systems], 5. [Deep Earth], 6. [Magnetic field], and 7. [Human impact]. These same seven challenges were then used as a basis to determine ESI-related science priorities in *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space* (National Academies of Sciences, Engineering and Medicine, 2018, https://nap.nationalacademies.org/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth). The ESI chapter summarizes highlighted accomplishments of the past year that respond to addressing these seven *CORE* challenges and associated *Decadal Survey* goals. Below are highlights of ESI Focus Area funded research accomplishments that have matured over the past year and represent research that has been funded over the past several ROSES cycles. Referenced ESI publications are also archived on ESDpubs (https://esdpubs.nasa.gov/pubs_by_program - select Earth Surface & Interior Program).

The scope of NASA's Earth Surface and Interior focus area (ESI) falls largely under the 1.1.8 "characterizing the behavior of the Earth system" performance goal. This includes the observation, analysis, and interpretation of any Earth surface or interior property or process using satellite, airborne, or associated ground instruments, along with computational and other assessment tools. Publications under this category contribute to improving interpretations of primarily space-based and remote sensing observations, identifying and addressing noise and other error sources, as well as the ability to characterize features related to the Earth surface and interior, such as mineral mapping, identifying earthquake deformation and source properties, and determining the presence and drivers of fluctuations in gravity and/or the electromagnetic field. In 2024 ESI had an increase in support of Earth System Observatory (ESO) missions, with publications supporting the Surface Biology and Geology (SBG), Mass Change (MC), and the NASA-ISRO SAR (NISAR) missions. ESI also continues a steady increase in multi-parametric data being used to resolve issues ranging from characterizing hazard monitoring data to better interpreting deep earth processes. It is believed this is the result of increased accessibility of data and algorithms and communication within the ESI community.

Lithospheric Processes and Properties

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. Lithospheric processes and properties research results in the past year addressed four of the seven *CORE* challenges [1. Plate boundaries, 2. Tectonics and surface processes, 3. Solid Earth and sea level, and 7. Human impact].

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.

Smith (2023) used InSAR data to study subsidence from groundwater depletion in the San Joaquin Valley, CA. They found that the region with the largest subsidence had shifted from the Kettleman City/Los Banos region in the west and to the Tulare/Pixley/Corcoran region in the south. They proposed that this shift was caused by historical pumping and subsidence in the west creating a form of "stress memory" in the aquifer that made it more resistant to subsidence during the recent drought event. However, should groundwater pumping continue at its current rate, stress in the aquifer will increase beyond previous level and the author believes subsidence in both of these regions will be substantial. Swarr et al, (2024) used GNSS data on mountainous watersheds of western US to monitor changes in terrestrial water storage across large regions in near real-time. They demonstrated that regions experiencing systematic and large-scale variations in water storage exhibit significant differences in predicted displacement (over 20 mm) depending on the choice of Earth model and independent data (e.g., altimetry, gravity) can be used to refine the model needed. The authors suspect that as this approach becomes increasingly utilized to inform decision-makers, pointing to the need for a deeper understanding of the assumptions and uncertainties of the models used to translate between geodetic measurements and estimates of water storage.

Anthropogenic Deformation

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

In order to better analyze how subsidence within Mexico City is impacting its infrastructure and Metro system Solano-Rojas et al. (2024) used InSAR data to identify which zones have been impacted and how subsidence will continue in the future. They found locations where the consequences of subsidence had compromised the train's braking safety design, increased railway flooding hazard, produced railway bending, and reduced the conceived 50-year service life of the Metro's elevated overpasses. The author further suggests that additional studies are needed to quantify the magnitude and extent of subsidence affecting the Metro system's widespread infrastructure issues. Henning et al., (2023) combined InSAR with oil production and injection data to study induced seismicity in the Delaware Basin in west Texas and southeast New Mexico from 2015 to 2021. They observed what they consider to be clear evidence of induced seismicity including uplift from reservoir swelling, subsidence from reservoir contraction, and the development of linear features that are indicative of faulting associated with oil production activities.

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.

Han et al. (2024) used GRACE and GRACE-FO data to measure changes in the Earth's gravity field to determine redistribution of mass from water, ice, and the solid Earth from earthquake events. They determined that gravity changes after shallow (<60 km) earthquakes involve significant volumetric changes within the crust as well as vertical deformation whereas thrust faulting intermediate events produce significantly different gravity signatures due to higher resistance of rocks to volume change. This study demonstrates the contrasting examples of gravity changes depending on depth of ruptures, which relate directly to the compressibility of rocks, and reiterates the importance of volume change in large-scale gravity changes.

Mineralogy

Using image spectroscopy techniques, satellite sensors acquiring imagery in the VNIR, SWIR, and TIR wavelengths can determine surface and aerosol compositions. Recently both the ISS based Earth surface Mineral dust source InvesTigation (EMIT), a visible-short wave instrument, and the airborne Geological Earth Mapping experiment (GEMx), a visible-short wave and thermal infrared mission, made significant advances in collecting and processing spectroscopic data to better locate and map the location of surface minerals around the globe.

Li et al. (2024, Nature – Communications Earth & Environment) used spectrometry lab measurements of hematite, an iron-oxide mineral, to better understand how this mineral contributes to the radiative forcing climate model. The EMIT mission identified that hematite dominated solar absorption by dust particles, however current estimates of the absorption capacity of this mineral varies by over two orders of magnitude. The findings of the authors provided valuable constraints on the absorption potential of hematite, substantially narrowing its range of plausible values and providing insights that have implications for enhancing dust modeling and contributing to efforts in climate change mitigation and adaptation.

Soil Moisture

The increasing precarity of water sources globally motivates the need for more observations of surface hydrology and water use, including variations in soil moisture. Several methods, inducing those using TIR and InSAR data can be used to track surface soil moisture remotely. Lohman and Burgi (2023) used InSAR data to determine the amount of soil moisture in hyperarid regions from a series of precipitation events by examining changes in coherence before and after events. The authors presented a statistical model of the relationship between soil moisture and phase, and how the parameters of this relationship can be inferred from the InSAR observables. They suggest this model, which is based on previous events, will improve soil moisture estimations, better InSAR quality for subsequent events, and provide an overall decrease in noise for InSAR measurements commonly used in ESI related investigations.

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

Slow slip, also known as fault creep or aseismic slip, is a key mechanism of seismic moment release on faults. Discrete slow-slip events are significant because they provide a unique opportunity to probe the mechanical properties of fault zones. Materna et al., (2024) used InSAR and GNSS data to study shallow slow-slip events in the Imperial Valley, CA along two fault systems in 2023. They observed events at both faults with propagation speeds ranging from 0.4 to 9 km per day, which the authors note is similar to velocities observed in subduction zones. They note that future work is needed to help understand what physical properties, such as confining stress, frictional strength, fluid pressure, and fluid diffusivity, control the propagation velocity of a slow slip event.

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. Research this year is helping the scientific community better understand volcanic processes through the use of thermal and SAR remote sensing, additionally the community continues research into better understanding and monitoring submarine eruptions.

Satellite Land Surface Temperature (LST) measurements offer a valuable means of continuously monitoring volcanic regions, providing insights into a range of volcanic phenomena from subtle thermal changes due to gas emissions to active lava flows. In order to quantitatively identify thermal features related to volcanic activity Corradino et al., (2024) applied an isolation forest machine learning algorithm to MODIS data. This algorithm was evaluated on various volcanoes worldwide characterized by different levels of volcanic activity. Through this process the authors were able to identify and classify the thermal activity level, thereby associating the thermal state of the volcano with the level of concern regarding ongoing volcanic activity. Pailot-Bonnétat et al., (2023) used infrared images from ASTER and VIIRS preceding the period of unrest at Vulcano Volcano in 2021 to determine how hydrothermal systems can generate phreatic and/or phreatomagmatic explosions with little warning. The authors found that integrating remote sensing thermal data enabled precursory signals to be detected from February to June 2021 where seismic, degassing, and geochemical metrics found an onset of unrest in September leading to a raise of the alert level October 1. The authors point out that this demonstrates how multiparametric surveys can improve understanding of volcanic systems and better track and forecast unrest.

InSAR and Digital Elevation Models (DEMs) derived from satellite data have long proven to be critical tools for observing deformation related to volcanic unrest. DEMs are also necessary to correct for topographic error when processing InSAR data. Eiden et al, (2023) studied the impact of inaccuracies in DEMs from changes in topography during a volcanic eruption to determine how frequently DEMs in these locations should be updated to remain accurate. They suggest that DEMs should be updated at least daily for accurate measurement during explosive eruptions. Galetto et al., (2024) determine how effectively the TerraSAR-X, TanDEM-X, and PAZ SAR instruments can observe volcanic activity at 120 volcanoes across the globe. They found that for short temporal and perpendicular baselines, TDX/TSX/PAZ can also provide useful deformation data, even in presence of vegetation. However, as no global background mission currently acquires TSX/TDX/PAZ data at volcanoes their suitability for studying pre-eruptive unrest is limited. Gonzalez-Santana et al., (2024) used 9 SAR datasets from 5 different radar platforms and seismic noise correlations to perform a geophysical analysis on the 2021 eruption of Pacaya Volcano. They determined that eruptive activity beyond the summit area initiated or accelerated flank creep on the southwest flank. The authors also concede that there might be contributions to the signal from lava flow compaction and seasonal tropospheric water vapor variations. This study demonstrates the challenges of coherence loss during periods with widespread lava effusion and ash fall, and the advantages of performing time-series analysis on shorter subsets of time to retain more pixels in times of lower volcanic activity.

A significant amount of volcanic activity on Earth occurs as submarine eruptions. These eruptions can have an impact on the atmosphere, create ashfall, tsunamis, and pumice floating rafts that can be hazardous to ships and coastal infrastructures. However, understanding, characterization, and monitoring these eruptions is still early in its developmental stages due to their submarine locations. Kelly et al., (2024) measured airfall volume of the 15 January 2022 eruption of Hunga Tonga-Hunga Ha'apai (HTHH) volcano by using estimates derived from comparing ocean color changes as seen in MODIS imagery to fall deposit thickness in the Kingdom of Tonga. Using a new developed method which fits a linear relationship between ash thickness and ocean reflectance they found a minimum airfall volume estimate of ~1.8 km^3. The authors acknowledge that this method does not account for the largest gain sizes, however they suggest that this new ocean-discoloration method is consistent with other independent measures of the plume and is effective for rapidly estimating fallout volumes in future volcanic eruptions over oceans.

Cascading Hazards

Often the occurrence of one natural hazard can lead to the triggering of a single or several new natural hazards, referred to as a cascading hazard. Howcutt et al., (2023) measured the impact of volcanic heat on glacier elevation at 600 glaciers located on and near 37 ice-clad volcanoes in South America. They demonstrate that 92% of glaciers near volcanoes melt more quickly emphasizing the need to exclude glaciers on, or near, volcanoes from glacier-climate investigations. The study also demonstrates the potential for glaciers as "volcanic thermometers" which results in volcanic-glacier monitoring contributing to our understanding of magmatic and thermal activity. Dunham et al., (2024) investigated the link between ground shaking and coseismic landslides by using surface slip measurements from the sub-pixel correlation of ASTER imagery. They developed simulated ground motions, including topographic amplification, to investigate these key factors that control the distribution of coseismic landslides. The authors found that the combination of strong peak ground motions, steep slopes, proximity to faults and rivers, and lithology control the overall spatial distribution of landslides.

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].

Interior

Kaini Shahvandi et al, (2024 – Nature, The Washington Post, The Atlantic) used satellite gravimetry data spanning two decades to quantitatively measure global-scale surface ice/water mass redistribution. They observed 120 years of data to determine how melting ice sheets and glaciers as well as changes in global water storage from over pumping groundwater and rising sea level might cause a change in the secular trend of the rotation of the Earth. This is due to either variations in torque at the core-mantle boundary, or dynamical feedback of the core in response to surface mass changes. They found that since the year 2000, days have been getting longer by 1.33 milliseconds per 100 years, which they believe is a direct result of anthropogenic impacts. Climatic contributions to the length of day will continue to increase and may surpass the lunar tidal friction contribution (+2.4 ms/cy) by 2100.

MacGregor et al, (2024) used seismic, gravity, magnetic, and topography data to map the geologic provinces beneath the Greenland ice sheet. They identified three subglacial regions in central and northern Greenland that cannot yet be reconciled with surface exposures. They also identified many valleys beneath the ice that seem to be very long and aligned with each other. The authors suggest that this research provides a new application for existing seismic, gravity, and magnetic methods which are applied to geophysical data to reveal subglacial structures with reduced influence from expert biases.

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 way these shifts occur can be used to calculate the properties of the mantle. Ivins et al., (2023) challenged the concept that repose to mass loading in purely elastic using observations made from GPS and GRACE data. To test this hypothesis they developed a mantle response Green's function that accounts for the vertical isostatic motion of the mantle caused by the acceleration of ice mass loss for Greenland and Patagonia. The authors determined that anelasticity corrections may be required for solid Earth vertical uplift in space gravimetric solutions for long-term hydrology and cryospheric change.

Vertical Land Motion

Sea level change is an increasing concern to island communities and locations that have many assets along the coast. These concerns can be exacerbated by vertical subsidence or improved by uplift; this is measured as vertical land motion (VLM). VLM is caused by either tectonic activity or by the loading of the crust from anthropogenic infrastructure and the occurrence of natural features such as glaciers, lakes, groundwater, and mountains. By understanding the extent and locations of VLM we can better understand how sea level change will impact the future. Huang and Sauber (2024) leveraged a new multi-primary pairing strategy for PS-InSAR to perform a robust estimation of coastal subsidence. This pairing method retains only consistent PS candidates across multi-primary substacks and solves for redundant velocity observations using
SVD-based inversion, similar to the conventional small baseline subset (SBAS) method. The authors suggest that this new method will increase the robustness of VLM estimates in challenging coastal environments where knowledge of local trends in subsidence is key to developing effective resilience measures to the drastic consequences of sea level rise.

Magnetic Field

Geomagnetic field modeling aims at building data-based mathematical representations, or models, of the various contributions to the total Earth's magnetic field measured at or near the Earth's surface. One of such contributions is the magnetic field generated by electric currents in the inner magnetosphere, including the so-called ring current. Fillion et al., (2024) developed a new model of the near-Earth magnetic field generated in the inner magnetosphere based on data collected in ground magnetic observatories from 1997 to 2022. This model provides an improved representation of the magnetic field generated in the inner magnetosphere during periods of moderate and high geomagnetic activity, including magnetic storms.

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. Geodetic Imaging research results in the past year addressed three of the seven *CORE* challenges [2. Tectonics and surface processes, 4. Magmatic systems, and 7. Human impact]

To improve the accuracy and validity of geodesy data, some groups have focused on reducing error of these data. Zebker et al., (2023) focus on methods for resolving tropospheric noise errors in InSAR data by characterizing both surface deformation and tropospheric noise from interferogram subsets with GPS and in situ validation. They chose different subsets of interferograms that use a common-reference SAR scene which then allowed them to quantify tropospheric noise and deformation signals. For the case study they performed in Hawaii their method shows that the observed InSAR phase on the south flank of Kilauea is due to a secular deformation signal, while the phase over Mauna Loa is mostly associated with tropospheric noise.

NASA-ISRO Synthetic Aperture Radar (NISAR) Science Team

The NISAR project was planning for launch, and the science team was active in developing and refining the algorithms for creating science products that would be suitable for validating the mission science requirements and creating validation methodologies. The science team has continued to work with the project to understand the data products characteristics and test them in the context of their algorithm workflows. In particular, the science team requested that the project generate sample products that could be used to generate higher level science products. Using data from the JAXA ALOS-1 and ALOS-2 satellites, as well as the ESA Sentinel-1 satellites, the project was able to create hundreds of time-series products that allow the testing of science algorithms in a variety of discipline areas – Antarctica, Western North America, Alaska, and known to be robust over a variety of land cover types, as well as offering other experimental methods. The project developed a cloud-based "on-demand" processing system for the science team to use with the NISAR data, collocated on the cloud.

The team has continued to socialize the impact NISAR will have through conferences and workshops. The NISAR Project and science team conducted a town hall meeting at the 2023 Fall American Geophysical Union meeting in San Francisco, CA, to update the community on the readiness of NISAR and the products. The project also organized dedicated conference sessions at the 2024 European SAR Conference (EUSAR 2024) and the 2024 International Geoscience and Remote Sensing Symposium (IGARSS 2024). The sessions were well attended, with the audience expressing great interest and anticipation of the vast free and open data sets NISAR will provide, at unprecedented analysis ready product levels on a global scale.

The applications science team continued to develop the community of early adopters and NISAR ambassadors. A series of virtual workshop update meetings was held to inform the extensive applications community of the project status and available tools and resources. The project also works closely with the OPERA project to coordinate product specifications that will facilitate adoption by the applications user community.

Following the success of the 2020-2023 UNAVCO virtual training classes for geodetic imaging, members of the NISAR science and algorithm development teams will repeat the training in August 2024. This year again, 150 students have been selected out of a pool of over 800 applications. The training will last 5 days, and use processing scripts and algorithms that will support NISAR geodetic processing on the cloud. In addition, the project conducted a special in depth short course for NISAR science and project team members on the fundamentals of synthetic aperture radar, held at Caltech, and recorded for future training opportunities. Students heard lectures from Professor Howard Zebker, a NISAR science team member, and developed SAR algorithms in computer labs to build practical understanding of the lecture material.

The Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) Facility

In the period between July 01, 2023 and June 30, 2024, UAVSAR logged 235 flight hours, collecting 144 L-band lines and 185 P-band lines. The countries imaged were USA, Greenland, Gabon, São Tomé and Príncipe, Cameroon, Ghana, Republic of the Congo, and Democratic Republic of the Congo. The UAVSAR team conducted 53 flights (21 L-Band / 32 P-Band) aboard the AFRC platform. Thirteen flights were pure-transit legs flown en route to either Greenland or Africa. The Project supported 14 Principal Investigators (PIs) performing research on a broad range of Earth Sciences disciplines: Applied Sciences, Hydrology, Cryosphere, Earthquakes, Landslides, and Terrestrial Ecology. The UAVSAR team additionally conducted engineering flights for instrument calibration, P-band ice sounding, and to prepare for bistatic experiments planned in collaboration with the Germany Space Agency, DLR.

In 2023, UAVSAR L-band observations of the Sawatch Mountains (CO) were employed by A. Handwerger and collaborators to map rock glaciers. Interferometric pairs between July and September were used to derive 3D-velocity maps and estimate rock glacier thickness. In April-May 2024, A JPL research team including A. Khazendar and A. Gardner led a deployment to Greenland. The P-band instrument imaged ice targets in different geographic regions to assess the performance in measuring subglacial topography and ice thickness. If successful, this ice-sounding system would provide critical parameters to simulate glacier dynamics in Greenland and Antarctica. In September-October 2023, UAVSAR's L-band radar joined NASA's FireSense campaign, during which agencies coordinated airborne and in-situ observations over Western forests selected for prescribed burns. L-band products will inform NISAR algorithms to map changes in fuel moisture and fuel load. The P-band instrument also supported the AfriSAR campaign in May-June 2024. AfriSAR is a coordinated effort with ESA (European Space Agency) and DLR (German Space Agency) to generate a common dataset over African ecosystems and foster collaborations between NASA, ESA, and African research communities. Selected study sites in West and Central Africa included coastal wetlands, biodiversity hotspots, and Congo Basin peatlands. This deployment was followed by an L-band deployment in July 2024. The co-located P+L acquisitions will provide a unique dataset to assess the performance of NASA's NISAR and ESA's BIOMASS observations for biomass retrieval of tropical forests. UAVSAR publications are continuously updated and can be accessed by visiting this web page: https://uavsar.jpl.nasa.gov/cgi-bin/publications.pl

UAVSAR is an aging system that must be modernized to maintain capabilities of the UAVSAR suite of radar instruments and its aircraft, set to be decommissioned in the near future. AIRSAR-NG has been identified as a successor along with a G-4 aircraft. It is anticipated that it will be able to support the upcoming LACCE EVS-4 campaign.

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.

Global GNSS Network

The NASA Global GNSS Network (GGN) continues to be updated and maintained as a state-of-the-art scientific GNSS network, providing high quality, multi-GNSS measurements to NASA and researchers throughout the world. The GGN is integrated with the International GNSS Service (IGS) Network and supports JPL's Global Differential

GPS (GDGPS) enterprise. Ongoing efforts are required to ensure the GGN is in compliance with the latest NASA IT security requirements. The GGN is coordinated with Goddard Space Flight Center's (GSFC) Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) network activities. In the past year, two, high value GGN sites at Easter Island and Guam were returned to service and contributing measurements.

Global Differential GPS (GDGPS)

GDGPS standard products are now available to the public through NASA's Crustal Dynamics Data Information System (CDDIS) which provides free public access. In addition, GDGPS continues developing software and enhancing services that combine the user's GNSS measurement with real-time GDGPS corrections to provide high-precision real-time point positioning.

GDGPS is also collaborating with the EarthScope Consortium which will use GDGPS real-time corrections to validate positioning products from other solution providers for "ShakeAlert". ShakeAlert promises to provide earthquake early warnings and could allow subscribers enough warning to prepare. GDGPS continues to partner with the International GNSS Service Central Bureau (based at NASA JPL) to promote and advocate for use of GDGPS in other disaster risk reduction applications.

Blewitt (2024) used GDGPS to improve the accuracy of the process of converting geocentric Cartesian to conventional geodetic coordinates by 3 orders of magnitude than other published non-iterative methods. They also transformed conventional geodetic coordinates into the practice system of "graticule distance" curvilinear coordinates. These are century-old issues and these improvements will improve historical reconstruction of benchmark occupation and local site tie analysis for reference frame integrity enabling geodetic timeseries to pull from a larger record of data with less errors.

Martire et al. (2024) discuss the JPL-GIM software to generate global ionospheric maps (GIMs) of total electron content (TEC) using measurements from multiple Global Navigation Satellite System (GNSS) constellations. They present five operational JPL GIM products (JPLG, JPRG, JPLI, JPLD, JPRT), highlighting JPLG and JPRG, our products routinely delivered to the International GNSS Service (IGS), and introduce a new near-real-time product (JPRT). The 2022 eruption at Hunga Tonga-Hunga Ha'apai was used to demonstrate JPL-GIM's high resolution capabilities, with 2 minute multi-GNSS data from approximately 100 stations and validations of these findings from independent datasets confirming an accurate reproduction of ionospheric variations across all latitudinal bands.

Martire L, Runge TF, Meng X, Krishnamoorthy S, Vergados P, Mannucci AJ, Verkhoglyadova OP, Komjáthy A, Moore AW, Meyer RF, Ijima BA. (2024). The JPL-GIM algorithm and products: multi-GNSS high-rate global mapping of total electron content. *Journal of Geodesy*, *98*(5), 1-25.

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.

Reprocessing of all GPS orbit and clock products from 1992 to present, to be consistent with the latest version of the International Terrestrial Reference Frame, is nearly complete. This reprocessing is time consuming but availability of GPS products in a consistent TRF is critical for researchers studying long term trends, such as plate tectonics and sea level rise.

The transition of the JPL Geodetic Analysis center to multi-GNSS operations continued with the initiation of operational production of daily, high-rate (30 second) Galileo + GPS orbit and clock products. The products represent a significant improvement over the previously provided low-rate products. Effort has been focused on Galileo since it has been shown that the combination of GPS + Galileo produces benefit over GPS alone in Precise Point Positioning. These products promise benefits for positioning dynamic platforms and for users interested in using GNSS to observe Earth’s atmosphere and ionosphere. The long-term goal is to produce products from all four major GNSS constellations for distribution to NASA missions and researchers.

Multi-technique analysis software tools in GipsyX (GNSS, SLR, VLBI and DORIS) were exercised and validated in TRF research and showed good results. The plan is to continue to exercise and refine these capabilities by demonstrating operational updates of a multi-technique TRF in the future.

GSFC Geodetic Analysis Centers

The ILRS, IVS, and International DORIS Service (IDS) Analysis Centers at GSFC processed geodetic data from 2021 to 2023, and submitted geodetic products for combination into the latest extension of the ITRF. The GSFC ILRS Analysis Center also reprocessed LAGEOS-1, LAGEOS-2 and the Etalon satellites from 1993 to 2023, to estimate the error and bias models used with the new ITRF, taking into account updated station-configuration-dependent SLR ranging systematics. The GSFC IVS Analysis Center processed 568 Legacy S/X sessions, and 100 VGOS sessions for the period 2021–2023, which included new antenna gravity deformation models for several VLBI stations. Processing of the daily VLBI Intensive sessions was automated, reducing the time required to deliver the data products as part of the US National Earth Orientation Service. A study to compare the legacy VLBI to VGOS intensives was also performed that demonstrated the new VGOS data products are an improvement over the older systems. The GSFC DORIS Analysis Center continued to routinely process DORIS data to six satellites (Sentinel-3A & 3B, Sentinel-6A, Jason-3, Cryosat-2, and Saral) and deliver operational products on a routine basis that include daily estimates of DORIS station positions and Earth orientation parameters. New and improved atmosphere density models were tested to better account for atmospheric drag and respond better to geophysical inputs during periods of higher solar activity.

NASA Space Geodesy Network

NASA GSFC continued to manage, operate, and maintain the NASA Space Geodesy Network (NSGN), exceeding levels of scientific data output achieved in prior years. The International Laser Ranging Service (ILRS) Central Bureau at GSFC also coordinated and set tracking priorities for the global-international SLR network. The 7 NASA SLR stations (California, Maryland, Hawaii, Australia, Peru, South Africa, Tahiti) tracked three classes of Earth satellites: (1) Low Earth Orbit (LEO), science-related satellites, (2) geodetic satellites whose data support development of the International Terrestrial Reference Frame and low degree harmonics of the Earth's gravity field such as LAGEOS-1, LAGEOS-2, LARES, LARES-2 and the Etalon satellites, and (3) the GNSS satellites. The LEO satellites supported by SLR include (i) high priority altimetry satellites such as Sentinel-6A Michael Freilich, ICESat-2, Surface Water Ocean Topography (SWOT), Jason-3, and Sentinel-3A & Sentinel-3B; (ii) the GRACE Follow-On Earth gravity mapping satellites, and the satellites of the Swarm constellation supporting that continuously map the Earth's magnetic field from orbit; and (iii) Synthetic aperture Radar mapping satellites such as Tandem-X, TerraSAR-X and PAZ. In 2023, the NSGN provided a quarter of the global SLR data for the LAGEOS-1 & LAGEOS-2 satellites that forms the basis of the SLR contribution to the International Terrestrial Reference Frame (ITRF).

SGP continued to operate three next-generation VLBI Global Observing System (VGOS) stations (Manyland, Texas, Hawaii) and two legacy VLBI stations (Hawaii, Brazil). The VGOS and legacy VLBI "Intensives" program continued to produce daily measurements of the variation in Earth rotation compared against standard clock time, an essential data product used for spacecraft navigation and global positioning, navigation, and timing services. The International VLBI Service for Geodesy and Astrometry (IVS) Coordinating Center at NASA GSFC continued to plan and schedule the global VLBI observations. This coordination included over 100 24-hour VLBI sessions that were used to produce precise Earth Orientation Parameters and Terrestrial Reference Frame products.

SGP began facility developments at the NSGN site in Brazil in preparation for the deployment of a new VGOS station with operations planned to start in 2025. The antenna was successfully manufactured by Calian InterTronic Inc., passed Factory Acceptance tests, and is ready to deploy to the site at Fortaleza once the facility work is complete. Deployment of a next-generation Space Geodesy Satellite Laser Ranging (SGSLR) system to Svalbard progressed with the successful installation of the Gimbal and Telescope Assembly at Ny-Ålesund and the start of Integration and Test of the rest of the system at GSFC.

Terrestrial Reference Frame Combination

A JPL produced Terrestrial Reference Frame solution, JTRF2020, using Geodetic network solutions from the four major Geodetic techniques, was delivered to the International Earth Rotation and Reference Systems Service (IERS) as part of the ITRF2020 effort. An update to JTRF2020 is in progress and will use products from the International Association of

Geodesy (IAG) Services also being used to update the International Terrestrial Reference Frame (ITRF). The JTRF2020 solution and, when available, updated JTRF2020 solutions will also be available on the JTRF Website, www.jpl.nasa.gov/site/jsgt/jtrf/.

A research TRF solution was completed, and results compare favorably to those from ITRF2020, the international standard. If ultimately successful, this approach could drastically reduce the cost of maintaining a high quality TRF. A high quality TRF solution using this method could be maintained by a single analysis center, instead of the ~30 currently required for maintaining the ITRF. The method also would minimize the need for expensive ground stations, such as those required for SLR and VLBI measurements.

Section 1.1.8.5 Water and Energy Cycle Focus Area

Introduction

NASA ESD's Water and Energy Cycle focus area (hereafter, WEC) supports investigations of the distribution, transport, and transformation of water and energy within the Earth System through Earth observing missions, airborne field campaigns, directed research at NASA Centers, ROSES competed research programs, and support for the World Climate Research Programme (WCRP) International Global Energy and Water Exchanges (GEWEX) Project Office (IGPO). WEC investments focus on improving remote sensing techniques and prediction of terrestrial water stores and fluxes such as soil moisture, snow, groundwater, streamflow, evapotranspiration, as well as feedbacks between land and atmospheric circulations at diurnal to seasonal timescales and meso- to synoptic spatial scales. Of NASA's Earth Observing fleet, the following missions are central to WEC science: Soil Moisture Active/Passive (SMAP; 2015–present), Global Precipitation Measurement (GPM; 2014–present), Surface Water and Ocean Topography (SWOT; 2022–present), Gravity Recovery and Climate Experiment (GRACE; 2002–2017), and Gravity Recovery and Climate Experiment Follow-On (GRACE-FO; 2018–present). WEC also supports development of surface water quality remote sensing approaches, which are becoming increasingly enabled by multi-satellite/multi-sensor SWOT, Landsat, and commercial satellite approaches. By enhancing observations, understanding, and modeling of the water and energy cycle, WEC activities strengthen the scientific basis for related ESD Earth Action programmatic activities in Water Resources and Agriculture.

In 2023, WEC supported concluding field work to its fourth Snow EXperiment (SnowEX: https://snow.nasa.gov/snowex) that comprised four campaigns in a period of six-years, 2017–2023). SnowEx field campaigns were designed to advance snow remote sensing both in theory and practice. The October 2023 activity was the low-snow bookend to the Spring 23's high-snow season. The campaign spanned Fairbanks, Upper Kuparuk-Toolik, and Arctic Coastal Plain sites and featured ground-based snow, soil, and vegetation sampling coincident with airborne Snow Water Equivalent Synthetic Aperture Radar and Radiometer (SWESARR), lidar, and stereo imagery. All ground and airborne datasets are made publicly available through the NASA DAAC at the National Snow and Ice Data Center (NSIDC). An August 2024 WEC-supported NASA Community Snow Meeting at the University of Colorado-Boulder marked the beginning of a formal SnowEx-informed review of the new state-of-the-science in snow remote sensing and modeling.

Terrestrial water storage

The GRACE and GRACE/FO satellite gravity missions provide measurements of Earth's gravity field, which can be used to derive estimates of terrestrial water storage (TWS) change within 1-2 cm equivalent water depth/month at 350-400 km scale horizontal resolution. Global GRACE TWS anomalies have declined at a rate of 1.02 cm/yr since the record began in 2002, reaching a new low of -9.94 cm in 2023 (Li and Rodell, 2024). Changes in TWS are shown to strongly correlate with changes in global temperature (Li and Rodell, 2023). Ninety percent of the 0.80 cm global TWS loss in 2023 is attributed to direct and indirect anthropogenic effects (i.e., ice sheet and glacier ablation, and groundwater withdrawals for irrigation). The remaining 10% of TWS loss is attributed to natural variability (i.e., precipitation, temperature, and modes of climate variability). Whereas TWS losses in 2023 were partly offset by gains in eastern Antarctica, Li and Rodell (2024) point out that continued TWS gains in that region are not expected given emerging signs of ice shelf destabilization.

Based on their assessment of the GRACE TWS timeseries, Li and Rodell (2023) conclude that both wet and dry extremes became more severe over the period from 2002-2021 —for temperate, tropical, dry, and continental climate zones alike. For example, intensification of continental zone wet events in Eurasia coincided with increases in fall−winter precipitation, earlier spring snowmelt, and thawing of permafrost. Intensification of continental zone droughts coincided with increased evaporative demands, vegetation heat stress, and large-scale groundwater pumping. The value of GRACE TWS as a standalone or complimentary dataset for extreme event detection and diagnosis has been demonstrated in several recent WEC-supported studies.

Using GRACE, Hall et al. (2024) calculated a 68.7 km^3 loss of groundwater in the U.S. Great Basin from 2002–2023. That amounts to two-thirds as much water as the entire state of California uses in a year and about six times the total volume of water that was left in Lake Mead, the nation's largest reservoir, at the end of 2023 (i.e., 10.9 km^3). Even record snowfall/snowmelt in 2022−2023 did not offset the Great Basin's dramatic groundwater level declines. Broadscale, long-term groundwater level declines observed across the southwest U.S. are attributed to increased evapotranspiration, increased groundwater withdrawals, streamflow diversions, and decreased groundwater recharge (Hall et al. 2024).

Carlson et al. (2024) used GRACE to study groundwater declines in California's Central Valley Aquifer. Applying a hybrid physics-based stochastic model, they successfully demonstrated a new GRACE TWS downscaling approach using Global Navigation Satellite System (GNSS) elastic vertical displacements and Interferometric Synthetic Aperture Radar (InSAR) measurements of poroelastic deformation. Based on their combined GRACE-GNSS-InSAR model, 20.4 +/− 2.6 km^3 of groundwater was estimated lost from the semi-confined to confined portion of the Central Valley Aquifer during California's August 2019 – September 2021 drought.

Martens et al. (2024) demonstrated California's TWS seasonal variability is largely explained by early- or pre-growing season atmospheric river frequency. Based on their GNSS-inferred TWS estimates, the ten or more incident atmospheric rivers between 25 December 2022 and 17 January 2023 added approximately 30 km^3 of TWS to the Sierra Nevada and approximately 60 km^3 of TWS to the Sacramento-San Joaquin-Tulare Basin. These gains amount to double the average October–March TWS gain over the preceding 17–years.

Streamflow

WEC-supported streamflow remote sensing and modeling research is advancing in new directions due to impending availability of SWOT data products (Fu et al. 2024). SWOT offers traditional nadir and novel swath estimates of surface water elevation, which when combined with estimates of channel geometry, roughness, and slope, can be used to to estimate streamflow. Surface water height–discharge relationships can prove especially accurate when based on high-accuracy DEMs, channel surveys, and recent field-surveyed height–discharge curves. Furthermore, SWOT surface water elevation heights, together with Landsat and Sentinel inundation area estimates can be assimilated into global hydrologic models along with other land surface variables (i.e., snow, vegetation, soil moisture, and groundwater) to constrain river discharge and contributing upland area runoff estimates.

SWOT-based discharge estimates will build-on research findings from other satellite sensors. For example, Barinas (2024) use aboveground biomass and canopy height measurements from NASA's Global Ecosystem Dynamics Investigation (GEDI) on the International Space Station to compute roughness coefficient Manning's *n* for 4,927 distinct floodplains in the continental U.S. The use of GEDI-derived *n* values yields significantly more accurate reach-scale floodplain flow predictions when compared to predictions using estimates of *n* based solely on land cover. Planned NASA LDAS implementations with SWOT data assimilation will also benefit from a more representative Manning's *n*; Manning's *n* is a critical input to the Muskingum-Cunge method-based Hydrological Modeling and Analysis Platform streamflow routing routine of NASA's LDAS.

Kugler et al. (2024) demonstrate the application of SMAP for streamflow estimates. Their approach exploits the fully polarimetric capability of SMAP by combining day and night SMAP brightness temperature observations and the forward and backward scans of the conical scan for daily streamflow estimates. The feasibility of the approach is demonstrated for 150 satellite gauging reaches globally with 14 reaches supporting comparison to available in-situ river gauging data. Results yield R-squared values of 0.75 for SMAP streamflow, which exceeds that of 0.68 for streamflow calculated in the same manner using *ESA's* Soil Moisture and Ocean Salinity (SMOS) measurements. Research is underway to use SMAP (and SMOS) to compliment future SWOT and other altimeter-based streamflow estimates.

Dolan et al. (2024) used Landsat to track summertime functional lake-to-channel connectivity of 10,362 lakes in Arctic Canada's Mackenzie River Delta between 1984–2022. Functional lake-to-channel connectivity refers to the ease with which sediment-laden water is transported from distributary channels into deltaic lakes. Connected lake area during the 2-weeks following peak discharge is found to be twice that of previous estimates, which indicates much larger influence of connected lakes on water movement through the delta than previously thought. They find, on average, that connected lakes store 7% of riverine floodwater. As the Arctic hydrological cycle responds to climate change, this work lays a foundation for tracking the movement of water and the sediment it carries, from the Mackenzie River watershed to the Beaufort Sea.

Brinkeroff et al. (2024) used a simplified model to study another similarly transient hydrologic phenomena: ephemeral streamflow. Ephemeral streams only flow 173, 46, and 4 days per year on average in the eastern, western, and southwestern U.S., respectively.

However, the study shows they contribute approximately 55% of the total discharge from USGS level-four (i.e., HUC4) drainage basins. The findings illustrate the important role that ephemeral streams play in the delivery of water, nutrients, and pollution into perennial water bodies. Further research across diverse biomes is needed to improve understanding of the volume and timing of ephemeral streamflow, and this work could be greatly enabled by NASA satellite remote sensing including SWOT.

Soil moisture

NASA's SMAP mission employs L-band radiometer observations with a spatial resolution of ~33 km to produce global soil moisture products at various spatial and temporal resolutions. Despite failure of its active radar three-months into the mission, SMAP has and continues to support impactful scientific discoveries and an ever-expanding array of applications. The SMAP soil moisture retrievals products have been continuously refined and expanded over time by the mission's science and applications team, including through integration with GRACE TWS and European Space Agency Sentinel SAR data.

Xing et al. (2023) show that the accuracy of current 9-km SMAP Enhanced Level-3 soil moisture estimates match that of ECMWF ERA-5 Land reanalysis soil moisture over non-forested sites (i.e., median ubRMSE of 0.07 ±0.02 m3/m3). Heavily forested sites preclude accurate soil moisture retrievals at SMAP's L-band given canopy emission, scattering and attenuation of the soil emission as demonstrated by Cho et al. (2024) in the Amazon rainforest. However, Wang et al. (2024) provide one potential path to overcome dense canopy retrieval challenges: maximum entropy production theory. They present a novel algorithm for simultaneous retrieval of soil moisture and vegetation water content from a single polarization of L-band brightness temperature based on the maximum entropy production theory of radiative transfer. Initial results of the proposed theory and algorithm are promising.

The 1- and 3-km resolution SMAP-Sentinel active-passive high resolution soil moisture product, which combines data from the SMAP L-band radiometer and the Copernicus Sentinel-1A and Sentinel-1B C-band SAR, supports hydrological and agricultural applications that were previously unsupported by coarser resolution radiometer-only products. However, in some agricultural regions the product has large errors. Singh et al. (2024) hypothesize these errors are partly attributable to unrepresentative, NDVI climatology-based vegetation optical depth parameters being used in the retrieval. They successfully remedy this limitation by incorporating new, fine-scale estimates of vegetation optical depth from Sentinel-1A/1B cross polarization backscatter data into the SMAP-Sentinel soil moisture retrieval. The revised approach significantly improves the accuracy of the SMAP-Sentinel product by reducing both bias and error standard deviation compared to retrievals based on vegetation optical depth derived from the NDVI climatology.

Soil moisture is a limiting factor of ecosystem function in arid and semi-arid environments. An open question is how ecosystems use moisture along the soil vertical profile. Feldman et al. (2024a) address this topic using NASA 70 m resolution ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station retrievals of land surface temperature and in-situ soil moisture measurements at different soil depths. Their work reveals that ecosystem water use decreases with depth; over 90% of sites sampled show significant land surface temperature coupling with soil moisture shallower than 20 cm. Only one-third of sites exhibit significant land surface temperature correlations with soil moisture deeper than 50 cm. Overall, the median depth of peak ecosystem water use is estimated to be 10 cm, though forests have more common peak interactions with deeper soil layers (50–100 cm) in 37% of cases.

Snow

Snow plays a critical role in the terrestrial Water and Energy Cycle. Radiatively, it cools the near surface air and insulates the soil below. Hydrologically, its melt timing influences spring runoff and vegetation green-up, and spring-to summer soil moisture dry-down. The 2017 NASEM Decadal Survey includes snow reflectivity as part of a designated Surface Biology and Geology mission. whereas snow depth and snow water equivalent are classified as “explorer” variables due to low technical readiness of the corresponding retrieval science for these variables. Recent WEC-supported publications, many of which hinge on NASA SnowEx campaign data for validation, demonstrate a pronounced step change in snow depth and SWE retrieval capabilities. Besso et al. (2024) show improved accuracy ICESat-2 mountain snow depth retrievals are achievable using the SlideRule Earth service for on-demand, customized site-specific ICESat-2 data processing in the cloud. Xu et al. (2024) investigate bistatic scattering characteristics needed for a proposed signal-of-opportunity P-band 2024 NASA Earth System Explorer SWE mission concept. Oveisgharan et al. (2024) and Palomaki and Sproles (2024) demonstrate promising results from InSAR-based SWE retrievals using Sentinel and UAVSAR, respectively. These two publications open the door to the possibility of having a NISAR SWE dataset, which would be suitable for scientific investigation.

Steep mountainous terrain, dense forest canopies, cloud cover, wet snow, deep snow, cloud cover, and sparse repeat coverage can each confound snow depth and SWE retrievals to varying degrees, depending on the sensor. For example, InSAR at C-, L-, and X-, and K-band are much more sensitive to vegetation effects than P-band; lidar is precluded by clouds; Ku-band has sensitivity to shallow snowpack SWE whereas X-band is less sensitive for shallow snow conditions but more capable for deep snow SWE. The remote sensing community has shown that SWE retrieval coverage and accuracy can be improved through multi-sensor and hybrid physical-statistical model approaches.

Borah et al. (2023) revolutionized dual X- and Ku-band SWE retrieval science with two new algorithms that do not require accurate priors on scattering albedo nor grain size. For context, uncertainty in initial snow grain size was the single greatest limitation of the X- and Ku-band SWE retrieval algorithm concept from ESA’s Earth Explorer-7 (2009) Phase A mission concept: Cold Regions Hydrology High-Resolution Observatory, and a large reason why snow depth and SWE received “explorer” classification in the 2017 Decadal Survey.

Dual frequency X- and Ku-band SAR single platform (Cho et al., 2024) and small constellation (Pflug et al., 2024) observing strategies were explored thoroughly with NASA LIS-based OSSEs. For the western U.S., Pflug et al. (2024) reported improved average SWE biases at maximum snowpack timing in shrub, grass, crop, bare-ground, and wetland land cover types from 14% to within 1%. For the mountainous Colorado subregion, Cho et al. (2024) reported attainable RMSE improvements of about 20% for SWE up to 600 mm and tree cover fraction up to 40%.

Singh et al. (2024) used SnowSAR SnowEx 2017 data to develop and validate another dual X- and Ku-band SAR SWE retrieval approach called BASE, or Bayesian-based Algorithm for SWE. BASE comprises a physical radar model and a statistical Bayesian inference model. The radar model represents the relationship between snowpack conditions and volume backscatter. The statistical model estimates the joint probability distribution of volume backscatter measurements, snow density and snow depth, and physical model parameters. The Bayesian prior distributions are derived from a multilayer snow hydrological model that has inputs of downscaled numerical weather prediction forecasts. In limited comparisons with SnowEx snow pit observations, BASE SWE estimates achieved absolute residuals of 5-7%. Pan et al. (2024) applied an extended version of BASE using data from the Nordic Snow Radar Experiment in which case an average SWE RMSE of less than 30 mm was achieved compared to 50 mm SWE RMSE from the snow hydrological model.

High Mountain Asia

NASA ESD has had dedicated ROSES solicitations in 2015 and 2019 focused on High Mountain Asia (HMA) in recognition of the lack of observations and limited understanding of the sensitivity of the regional snow- and glacial-fed ecosystems and over two billion inhabitants to climate change.

With support from the HMA program, Prusevich et al. (2024) created an improved MERIT-Plus river network database that for-the-first time includes classification of basins as exorheic or endorheic. Endorheic basins, which do not spill over their topographical depression boundaries or link to the seas, cover approximately 20% of the world's land surface. The new river network database can help ensure these basins are represented in models accordingly, and ultimately, improve understanding and modeling of the effects of climate change on: hydrology in arid regions, trends in gravity anomalies, management of water resources, preservation of ecosystems, and evaluation of endorheic lake storage dynamics.

Flores et al. (2024) demonstrated new detection capability for narrow proglacial headwater streams across HMA using PlanetScope 3 m resolution imagery. Headwater streams transport nutrients, sediment, and mineral-rich groundwater. In HMA, streams also funnel glacier and snow melt to sustain continuous water supply for the downstream region. Mapping of these streams was previously unachievable because their widths were exceeded by Landsat and Sentinel-2 resolutions of 30 m and 10 m, respectively. The results show that computer vision techniques, not normalized difference water index thresholding or random forest techniques, offer the best path forward for global headwater mapping efforts; computer vision yielded surface area matches of 0.98 R-squared against manually labeled surface areas.

Zeller et al. (2024) applied PlanetScope, Sentinel-2, and Landsat data to analyze supraglacial lake dynamics in the Khumbu region of Nepal. There is great need to better understand and model these lake dynamics as part of a broader regional debris-covered glacier system given the severe danger that rapid drainage may pose to downstream communities, ecosystems, and infrastructure. The results reveal a pronounced annual cycle in supraglacial lake area, with lakes covering approximately twice as much area at their peak, pre-monsoon season extent than at their post-monsoon minimum extent. Four of eight glacier systems analyzed experienced significant decadal-scale expansion of their large, near-terminus lakes. The difference in annual maximum and minimum lake extent is of comparable or greater magnitude than decadal-scale changes, highlighting the importance of accounting for seasonality when interpreting long-term records of supraglacial lake area changes from temporally sparse observations.

Kim et al. (2024) highlight that like glacial lake extent, permafrost extent is also a critical observable across HMA, especially in the context of impacts to hydrology, ecosystems, and natural hazards. Whereas sparse in situ surface or borehole temperature measurements on the Tibetan Plateau support limited-area estimates, satellite remote sensing is essential to monitoring region-wide permafrost changes, including in the more remote reaches of the Tien Shan, Pamirs, and Himalayas. Applying a novel fusion of NASA MODIS and AIRS surface temperature data for clear-and full-sky scenes, respectively, Kim et al. (2024) estimates a total current HMA permafrost area of 1.69 (± 0.32) million km^2, across 15 mountain subregions. Furthermore, they provide a range of possible permafrost extents based on soil moisture and snow cover scenarios.

Hydrologic sensitivity to climate variability and change

Ongoing climate and global change are contributing to shifts in ecotones (e.g., arid and semi-arid zone boundaries) and storm characteristics. Since 1980, daily rainfall events have become more intense but less frequent over 36% of global land areas (Feldman et al. 2024b). Larger rainfall events and longer dry spells have complex and sometimes opposing effects on plant photosynthesis and growth, challenging abilities to understand broader consequences on the coupled water-energy-carbon cycle.

Feldman et al. (2024b) provide an extensive literature review on global plant responses to changes in rainfall frequency and intensity. The study specifically addresses how fewer, larger rainstorms are affecting plants globally. Based on evidence from field manipulation experiments, environmental observations, and biosphere process models they report that increased precipitation variability decreases plant growth in 53% of regions with relatively wet climates. In dryland regions, increased precipitation variability can have either positive (38% of drylands) or negative (29%) impacts on plant growth. Significant knowledge gaps remain regarding optimal rainfall frequencies for photosynthesis, the relative dominance of rainfall pulse and dry spell mechanisms, and the disproportionate role of extreme rainfall pulses on plant function.

Other WEC-supported scientists are also using NASA data and models to delineate hydrologic regimes and investigate ecosystem sensitivity to change. For example, Donahue et al. (2023) demonstrate the utility of SMAP brightness temperatures for monitoring landscape freeze-thaw transitions. Their deep learning model-based freeze-thaw classifications are shown to be consistent with ERA5 and in-situ weather stations more than 90% of the time. Koster et al. (2024) use a combination of NASA SMAP soil moisture, Atmosphere-Land Exchange Inverse (ALEXI) evapotranspiration, as well as ground station air temperature measurements to generate updated monthly maps of the water-limited, energy-limited, and combination regimes over the continental United States and across the world. Knowing where evapotranspiration is water limited, energy limited, or some combination of both is important because it indicates where accurate soil moisture initialization in a forecast system might contribute to more accurate forecasts of evapotranspiration and thus air temperature.

International GEWEX Project Office (IGPO)

The ESD-supported IGPO facilitates cooperation among over 2000 GEWEX researchers worldwide on over 50 projects aligned with the WCRP Strategy and Implementation Plan. GEWEX formally opens-up and engages with the full international climate research enterprise through large international science conferences every 4-6 years. Its 9th Open Science Conference took place from 7 to 12 July 2024 in Sapporo, Japan with over 900 registered attendees. The conference celebrated 30+ years of GEWEX research and set the stage for the next phase of research addressing WCRP challenges on water resources, extremes, and climate sensitivity. The week preceding the conference featured: GEWEX annual science panel meetings, an Early Career Researcher workshop on “Extremes in the water cycle and risks to society: Understanding ‘actionable’ information in hydroclimate research,” a space agency event to facilitate engagement between Early Career Researchers and representatives from international space agencies, and a Groundwater Workshop to tackle the challenges of constructing and applying hydrogeologic and groundwater flow models over large space and time scales. For the first time, the Open Science Conference included presentations by stakeholders motivated to advance science-informed adaptive planning in the areas of water availability and flooding.

Section 1.1.8.6 Weather and Atmospheric Dynamics Focus Area

The Weather and Atmospheric Dynamics Focus Area (WAD) uses NASA's existing satellite fleet to observe weather systems, produces 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 processes that produce weather, 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**,** WAD supports calibration and product generation for parameters such as global precipitation, atmospheric temperature and humidity profiles, atmospheric winds, and ocean surface winds. After data products are released, WAD also funds scientific investigations that analyze data to characterize the behavior of the Earth system with an emphasis on phenomena identified using satellite observations.

WAD funds research work that aligns with the 2017 Decadal Survey. This includes projects associated with development of the Atmosphere Observing System (AOS) that measure and characterize convection, concept development of the Planetary Boundary Layer (PBL), and field experiments and concept validation of three-dimensional (3D) winds. Significant progress was measured via peer-reviewed publications in addition to other metrics such as new or updated products released during the previous year.

WAD supported one field campaign over the evaluation period. The Airborne Lightning Observatory for Fly's Eye Geostationary Lightning Mapper (GLM) Simulator and Terrestrial Gamma-Ray Flashes (ALOFT) campaign was held in July 2023, which focused on lightning in the Gulf of Mexico. In addition, ALOFT data were used to validate observations from the International Space Station (ISS) Lightning Imaging Sensor (LIS) and the GLM on the Geostationary Operational Environmental Satellite (GOES)-16. Instrument test flights were also held for the upcoming Westcoast & Heartland Hyperspectral Microwave Sensor Intensive Experiment (WHyMSIE), which is scheduled for October through November 2024 and includes focused measurements for PBL research.

Characterizing Atmospheric Behavior

Characterization of Fires and Associated Atmospheric Conditions: The synergy of high-spatial resolution narrow-band imagers and hyperspectral infrared (IR) sounders allow for comprehensive observation and long-term global monitoring of fire characteristics and associated atmospheric changes on the pixel scale. Zhou et al. (2024) demonstrated methods to utilize pixel-scale fire observations from the Visible Infrared Imaging Radiometer Suite (VIIRS) and the IR radiance spectra from the Cross Track IR Sounder (CrIS) on the Suomi National Polar-orbiting Partnership (SNPP) mission to analyze the atmospheric conditions before, during, and after fires. Key findings indicated that CrIS has high fire sensitivity, and the corresponding CrIS atmospheric temperature, humidity, and trace gases were quantified. The work shows collocated imager and IR sounders provide a method to identify and monitor wildfires, reinforcing the value of integrated observations.

Fire Monitoring and Detection using Atmospheric IR Sounder (AIRS): The increasing rate of wildfires places a growing strain on ecosystems and global climate. Yu et al. (2024) assessed a method to detect wildfires using AIRS Version 7 Level 2 nighttime cloud-cleared radiance anomalies for hotspot analysis. The work is complementary to methods based on lower spectral but higher spatial resolution observations from other satellites and has promise for near real-time fire detection from space. Additional results found that there is more water vapor from the surface to the upper troposphere during the fire event because of biomass burning and an increase in air temperature.

Hyperspectral Infrared Radiance Climate Records: The NASA CrIS Level 1B project supports climate research by providing high-quality algorithms and software for long-term measurement records of the CrIS instruments. This team has made significant progress, including characterizing calibration artifacts in Joint Polar Satellite System 2 (JPSS-2) CrIS and developing a new calibration process. A new CrIS Level 1B software version (v4) with improved features will be delivered in Q3 2024. Updates to the current software addressed issues with the aging SNPP CrIS sensor and new beta products for JPSS-2 CrIS were released. In addition, research papers on CrIS radiance simulation (Borg et al. 2023) and comparisons with other infrared sounders (Loveless et al. 2023) were published.

Release of New CrIS Single Footprint Data Product: Level 2 and Level 3 products from the Single Field-of-View Sounder Atmospheric Products (SiFSAP) algorithm were generated for the CrIS from November 2011 to May 2021 and publicly released. SiFSAP has 3-times higher spatial resolution and 9-times denser data products comparing to current NASA and NOAA operational IR sounder products, which supports future weather and atmospheric dynamics research by revealing mesoscale atmospheric variations. The SiFSAP Level 2 products contain a variety of geophysical parameters retrieved from IR and microwave sounder measurements, including profiles of temperature, water vapor, trace gas species, as well as clouds and surface properties (Wu et al. 2023).

Combined Radiance Record from AIRS and CrIS for Climate Research: A combined radiance record from Aqua-AIRS and the three CrIS instruments now covers September 2002 to present. The Climate Hyperspectral Infrared Radiance Product (CHIRP) converts the AIRS and CrIS radiances, which have different channels and calibrations, into a homogeneous product that has effectively identical frequencies and radiometric calibration for both instruments. CHIRP data is publicly available at the GES DISC and the Amazon AWS Open Registry (AWS: "s3://nasa-chirp-tiling"), allowing researchers to use CHIRP data for climate trends, variability, and extrema with fast and low-cost cloud resources.

Enhanced Information on the PBL from Thermal and Microwave Sounders: Recent results have shown that the existing program of record AIRS-Advanced Microwave Sounding Unit (AMSU) retrievals of temperature and humidity can be enhanced in the PBL by employing deep learning, including new generative AI techniques (Milstein et al. 2023, 2024). These approaches enable uncertainty quantifications that can rigorously bound PBL sensing performance on a per-scene basis while fully accounting for prior knowledge of a realistic atmosphere. An effort to validate these newer approaches with truth data, including PBL-focused radiosonde data over the Southern Great Plains, is underway.

Characterizing Atmosphere-Surface Boundary Conditions

Cyclone Global Navigation Satellite System (CYGNSS) Ocean Surface Winds: Several ocean surface wind speed products were produced from CYGNSS data. The most used product for scientific investigations is the Science Data Record Fully Developed Seas (FDS) 10-meter, neutral stability, equivalent wind speed. The current version (v3.2) was released in March 2024. A new ocean surface wind speed product was also developed and released in March 2024. The Level 3 merged storm (MRG) wind speed combines the CYGNSS storm centric gridded winds, produced in the inner core of organized storms (Mayers et al. 2023), with a gridded version of the FDS winds away from the storm. The L3 MRG product eliminates the need to choose between different wind products depending on sea state development and the proximity to storms (Warnock et al. 2024).

CYGNSS Surface Energy Fluxes: Latent and sensible heat fluxes (LHF and SHF) at the ocean surface are functions of wind speed in addition to air–sea humidity and temperature differences. The CYGNSS FDS wind speed product, combined with reanalysis for thermodynamic variables, is used to produce LHF and SHF data products. The current version (v3.2) of the CYGNSS Ocean Surface Heat Flux product was released in June 2024 and is used in ongoing investigations of the Madden–Julian Oscillation (MJO), extratropical cyclone (ETC) genesis and development, and diurnal cycles of wind speed and precipitation. Diurnal variations in surface heat fluxes have been found to be leading indicators of convective activity and precipitation (Bui et al. 2023; Natoli and Maloney 2023; Riley Dellaripa et al. 2023).

CYGNSS Soil Moisture: The CYGNSS soil moisture product (v1.0) was released in 2020 and has been used in a wide array of investigations related to atmosphere-surface interactions (e.g., Lei et al. 2022; Wang et al. 2022; Liu et al 2023). An updated version (v3.2) of the soil moisture product was recently developed and released in June 2024. The new version incorporates the latest improvements in Level 1 calibration to improve long term stability. Momentum and heat fluxes at the atmosphere-surface boundary are strongly influenced by the near-surface soil moisture content and the updated product can also be used for flux studies over land.

CYGNSS Environmental Monitoring and Characterization

Inland Water Inundation Mapping: The ability of CYGNSS to finely resolve inland water bodies in day/night, clear/cloudy, and bare/vegetated surface conditions has enabled numerous investigations related to wetland inundation, modeling of methane production and the carbon cycle, and seasonal and episodic flooding (e.g., Chew et al. 2023; Downs et al. 2023). The inland water detection methodology itself also continues to be refined (e.g., Carreno et al. 2023a, 2023b).

Characterizing Tropical Cyclones

Describing Key Tropical Cyclone Measurements: Ricciardulli et al. (2023) summarized current measurements used by operational agencies for tracking and characterizing tropical cyclones (TCs) from space. New small- to medium-sized satellite microwave technologies such as the Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS), Temporal Experiment for Storm and Tropical Systems (TEMPEST), and Compact Ocean Wind Vector Radiometer (COWVR) provide

TC views comparable to operational sensors, but in much smaller and less expensive packages. Comments are also made for future satellite constellations.

Rapid Revisits of Precipitating Storms: Constellations of smallsat passive microwave sensors offer the potential for rapid revisits (i.e., overflights) of precipitating storms, including tropical convective systems and cyclones. You et al. (2023) compared precipitation estimates from the TROPICS Pathfinder, Advanced Microwave Scanning Radiometer 2 (AMSR2), Special Sensor Microwave Imager/Sounder (SSMIS), Advanced Technology Microwave Sounder (ATMS), and Microwave Humidity Sounder (MHS) to estimates from the Global Precipitation Measurement (GPM) Microwave Imager (GMI). Despite its small size, precipitation estimates from the TROPICS Pathfinder were as good, or slightly better than, estimates from the operational sounders, indicating significant potential for mapping of precipitation from smallsats.

Vertical Profile Information on Atmospheric Temperature and Humidity: In addition to precipitation, the TROPICS satellites provide vertical profile information on atmospheric temperature and humidity. Yang et al. (2023) found that TROPICS retrievals showed larger standard deviations in total precipitable water relative to reanalysis and ATMS retrievals, but comparable correlations and bias. For water vapor, TROPICS retrievals showed larger standard deviations in all situations. TROPICS calibration/validation efforts are still ongoing, and product quality is expected to improve as the calibration is updated.

Faster and More Accurate Retrievals of Geophysical Quantities via Machine Learning: Recent advances in machine learning (ML) offer the potential for faster and more accurate retrievals of geophysical quantities like temperature and specific humidity. Milstein et al. (2024) discussed ML approaches applied to thermodynamic retrievals from IR and microwave sounders and showed retrievals applied to TROPICS Pathfinder data through a cross-section across Hurricane Ida in 2021. Key findings indicate that the retrieval produces similar temperature and humidity profiles to reanalysis, capturing the warm core and high humidity within the storm. The retrieval was successful despite the strong scattering signature associated with cloud ice within the storm, potentially overcoming an inherent problem with physical retrievals in precipitating regions.

3D Lightning Mapping is Feasible with a Constellation of Low-Earth Orbiting Satellites

NASA is working in collaboration with Los Alamos National Laboratory to develop a satellite mission concept called CubeSpark, which will map the three-dimensional structure of lightning activity on a global scale. Recent simulations by Remington et al. (2024) of very high frequency (VHF) radio waves produced by lightning demonstrate the feasibility of this approach to geolocate the altitude of lightning flashes with a vertical uncertainty less than 1 km. This result is needed to resolve electrical charge regions important for studying severe weather processes and measuring the production of lightning-induced nitrogen oxides. Lang (2023) found that spaceborne sensors like CubeSpark, which could detect weaker flashes, would have significant benefits for characterizing thunderstorm evolution more accurately than LIS or GLMs.

Characterizing Convection and Precipitation

Time-resolved Characterization of Pre-Convective Atmospheres: The 3D fields of temperature and specific humidity retrieved by instruments such as AIRS are predictive of convection, but convection often triggers during the multi-hour gaps between satellite overpasses. Richardson et al. (2023) filled the hours after AIRS overpasses by treating AIRS retrievals as air parcels that move adiabatically along numerical weather prediction wind trajectories. Key results include the grid cells with highest CAPE and lowest CIN bins from the trajectory enhancement experiment were more than 50 times as likely to develop heavy precipitation (> 4 mm hr^{-1}), compared with the baseline probability from a random location. Their results support the development of similar products for operational atmospheric sounders to provide time-resolved thermodynamics in rapidly changing pre-convective atmospheres.

Goddard Profiling Algorithm (GPROF) for the Retrieval of Surface Precipitation and Hydrometeor Profiles: The Goddard Profiling Algorithm (GPROF) is used operationally for the retrieval of surface precipitation and hydrometeor profiles from the passive microwave observations of the GPM mission. The updated GPROF (V07) entered operational use in May 2022 and development is underway to improve the retrieval by transitioning to a neural-network-based algorithm (GPROF-NN). Pfreundschuh et al. (2024) found that the GPROF-NN retrieval produces reliable estimates of liquid precipitation over the US and annual mean precipitation was within 8% of gauge-corrected radar measurements. Although biases of up to 25% are observed over sub-regions of the US and the tropical Pacific, the retrieval reproduces each region’s diurnal and seasonal precipitation characteristics. The evaluation further showed that GPROF-NN retrievals have the potential to significantly improve the GPM precipitation retrievals.

Multiplatform Precipitation Feature Dataset: Bang et al. (2023) constructed a new Multiplatform Precipitation Feature (MPF) dataset that draws on the GPM Dual-frequency Precipitation Radar (DPR), ground-based radar from the GPM validation network, and space-based lightning measurements from the ISS LIS. One key new feature is that the dataset supports the storm-centric perspective that typifies ground-based analysis, but with the wider coverage and statistical capabilities of spaceborne datasets. Overall, the database enables cross-platform, broad statistical thunderstorm-centric analyses in addition to detailed single-storm case study reconstructions.

New Uses for Microwave Brightness Temperature Datasets: The fundamental passive microwave Brightness Temperature (TB) datasets from GPM and the entire set of constellation satellites continue to be exploited in new ways. Morvais and Liu (2023) related GMI TBs to GLM lightning flashes by using 4 years (2018–2022) of the GPM Precipitation Feature (PF) database. Artificial Intelligent (AI) Neural Network models were trained to classify PFs producing lightning in a 20-minute window for land, ocean, and coastal regions in addition to calculating flash rates of the PFs that produced lightning. When the global lightning distribution was computed by applying the AI models to the global set of PFs, it compared well to the lightning climatology from LIS and the Optical Transient Detector (OTD). This suggests that the use of passive microwave TBs can help to fill the gaps in lightning monitoring thanks to their global coverage.

Simulating Precipitation Microphysics in Tropical Cyclones: Precipitation microphysics in TCs are often poorly represented in numerical simulations, which ultimately affects TC structure, evolution, and prediction. Brauer et al. (2024) matched International Best Track

Archive for Climate Stewardship (IBTrACS) TC storm centers with corresponding GPM DPR overpasses for 112 TCs from 2014 to 2020 to identify cloud properties and associated precipitation processes. Results showed the highest storm top heights occurred in the Northwest Pacific and Indian Ocean. They also found differences in microphysical processes in TCs by distance from the storm center, ocean basin, and shear-relative quadrant. Application of these results could potentially improve the representation of cloud properties and the future accuracy of the DPR particle size distribution algorithm in TCs.

Comparing the Accuracy of Integrated Multi-satellitE Retrievals for GPM (IMERG) to Precipitation Estimates: Bogerd et al. (2024) compared the accuracy of IMERG to precipitation estimates based on Meteosat Second Generation Visible (MSG-VIS), MSG-Infrared (MSG-IR), and the non-governmental Trans-African Hydro-Meteorological Observatory (TAHMO) gauges across the Odaw catchment that encompasses Accra, Ghana for January 2020-July 2022. IMERG had difficulty capturing the strong spatial variability of rainfall required for flood forecasting but agreed well with TAHMO and MSG-IR for the annual totals, in addition to providing reliable daily and longer-interval totals overall. The authors suggested that MSG-IR and MSG-VIS could both be used to assess variability within individual IMERG gridboxes, which might support weather-regime-based revisions to the IMERG estimates.

Examining the Performance of IMERG Precipitation Products to Capture Rainfall Events: Bartuska and Beighley (2024) explored the potential use of GPM data in monitoring water supply infrastructure and performance of IMERG precipitation throughout North Carolina. Results show that the IMERG data identify events reasonably well with high probability of detection and low false alarm ratio for all Early, Late, and Final products. The findings support the potential use of Early and Late IMERG products in water supply monitoring or flood warning systems, where rapid estimates of precipitation characteristics are needed.

Evaluating Daily Precipitation in Fujian Province: Fan et al. (2023) evaluated daily precipitation at varying magnitudes in Fujian Province, China, by comparing IMERG products with surface precipitation station data for 17 typhoons that landed in the region after passing through Taiwan. Correlation coefficient analysis revealed that maximum daily precipitation performed best, followed by process total precipitation. Overall, IMERG's ability to detect heavy precipitation structure, intensity, and location is fair and has some reference value, especially for regions where conventional information is scarce.

Campaign for Characterizing and Understanding Wintertime Clouds and Precipitation

Measurements of Snowbands Within Winter Cyclones: The Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) was an Earth Venture Suborbital-3 (EVS-3) field campaign to study northeastern and midwestern US snowstorms. The overarching goals of IMPACTS were to understand the mechanisms associated with snowfall variability and snowband formation, organization, and evolution using airborne remote sensing measurements from aircraft flying within the clouds. IMPACTS collected data from over 35 winter storms that occurred in 2020, 2022, and 2023 and obtained over 55 hours of coordinated remote sensing and in situ observations. An overview article (McMurdie et al., 2022a) appeared in the flagship journal of the American Meteorological Society that describes the project and highlights results from the 2020 deployment. The 2022 deployment was summarized in McMurdie et al. (2022b).

More than 30 published articles document IMPACTS results and have advanced our understanding of snowfall and precipitation processes in winter ETCs, often focusing on mechanisms contributing to snowfall variability and snowband structure. Janiszeski et al. (2024) explored how horizontal kinematic flow structures within the comma head regions of two strong northeast winter storms can reorganize particle concentrations into snowband-like structures. Oue et al. (2024) documented microscale updrafts in Northeast coastal snowstorms that were forced by turbulence associated with vertical shear instability. Richter et al. (2024) explored the usefulness of passive microwave radiometer observations in detecting the horizontal structure in winter storms. Allen et al. (2024) showed how mesoscale pressure waves in the atmosphere can be detected with ground-based sensors and how in some cases these waves can modify clouds and precipitation in winter storms. Other characterization studies improved cloud and precipitation retrievals using IMPACTS data. Zaremba et al. (2024) developed a new cloud-top phase algorithm that can be applied to airborne or spaceborne lidar measurements. Grecu and Yorks (2024) showed how backscatter lidar, Ku-band radar, and submillimeter-wave radiometer measurements can be used synergistically to retrieve ice cloud measurements from space. Several more manuscripts highlighting IMPACTS results are in review.

Field Campaign and New Discoveries about Gamma-Ray Radiation in Thunderstorms

The ALOFT campaign took place during July 2023 out of Tampa, Florida and made major discoveries about the abundance of gamma-ray glows in tropical thunderstorms using the NASA ER-2. Originally thought to be up to 10,000 times rarer than lightning, terrestrial gamma-ray flashes (TGFs) instead were detected on most ALOFT science flights and appear to be related to the presence of low-level, longer-lived gamma-ray emissions known as glows. This increase in TGF frequency is due to a large population of weaker TGFs that are not detectable from current spaceborne platforms (Bjørge-Engeland et al. 2024).

ALOFT also discovered a new type of TGF-like event, called a Flickering Gamma-ray Flash (FGF), which unlike most TGFs is radio-quiet and not associated with optical output (Østgaard et al. 2024). FGFs started as ordinary gamma-ray glows, which experience sudden exponential intensity increases and turn into an unstable, flickering mode with a sequence of pulses. This discovery could be the missing link between the gamma-ray glows and conventional TGFs, of which the absence has puzzled the atmospheric electricity community for decades. Glows meanwhile were found by ALOFT researchers to be ubiquitous and highly dynamic within tropical thunderclouds, covering areas the size of thunderstorm complexes and lasting for hours in aggregate (Marisaldi et al. 2024).

Lightning Imaging Sensor Completes its Mission

On 16 November 2023, the LIS on the ISS completed its nearly 7-year (2017-2023) mission. The mission was highly successful and extended the Tropical Rainfall Measuring Mission (TRMM; 1998-2014) LIS global lightning climatology both in time and spatial coverage. During mission closeout, both LIS datasets are being harmonized and combined with the OTD (1995-2000) with the aim of producing a nearly 30-year climate data record of lightning from space. To assist with this merger, recent work quantified the absolute detection efficiency of ISS LIS at ~65% with TRMM LIS, where the latter was slightly more sensitive (Virts et al. 2024).

ISS LIS observations were combined with GPM validation network ground-based radar data to produce the previously mentioned MPF database that includes information about thunderstorm structure, vertical motions, and lightning (Bang et al. 2023). ISS LIS data have also been used to assist with the hunt for TGFs from space (Köhn et al. 2024). In addition, the long climate record provided by the LIS missions helps us to understand lightning variability in relation to phenomena like the El Niño-Southern Oscillation (ENSO). For example, Clark and Cecil (2024) found regional increases in lightning in subtropical South America and north-central Africa during El Niño episodes, while lightning tends to decrease in northern Brazil and southeastern Africa. This work has been extended to ground-based observations of cloud-to-ground (CG) lightning in the United States, which found that ENSO may be a useful predictor of US CG lightning activity during winter through spring months (Malloy et al. 2023). These results have direct implications for wildfire prediction and other societal benefits.

Short-term Weather Prediction and Transition to Operations

Enhancing the Short-term Prediction Research and Transition (SPoRT) Sea Surface Temperature (SST) Composite Product: The SPoRT SST Composite product was updated to anticipate the decommissioning of NASA's Aqua satellite. Updated product development includes incorporation of additional satellite observations as well as a global domain. In addition, a climatological anomaly product based on NASA's Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis was developed along with temporal trend products (i.e., 3-day, 7-day, 2-week). The product was revalidated against buoy observations and had high (0.99) correlation with a low mean difference from observations (-0.18 K) and root mean squared error (1.26 K). The SPoRT SST is used widely by stakeholders within the National Weather Service (NWS), National Ocean Service, the NASA Disasters program, universities, and the private sector for a wide range of applied research, decision-making, and ingest into models and private sector services. Expansion of the SPoRT SST products will provide derived information to inform applied research and decision-making, supporting NASA's Earth Science to Action goals.

Rapid Expansion of the SPoRT Streamflow-AI Product: The SPoRT Streamflow-AI product continues to demonstrate value in decision-making and mitigating the impacts of hazardous flooding events. As a product developed based on an NWS need for tools to anticipate flooding beyond 48 hours, Streamflow-AI has continued to expand and is now providing high-impact flooding forecasts for over 230 river-gauge sites for more than 30 NWS Offices. SPoRT has numerous Earth Action stories where the product provided flooding forecasts as much as 5 days in advance of an event, which has led to early and timely evacuation and road closure decisions that helped mitigate adverse societal and economic impacts. Continued development of a second model in underway for more complicated flash-flooding events.

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, we summarize here 10 papers from ACFA-sponsored research in the last year to (a) better understand and model dust emissions, ageing of biomass burning aerosols and cirrus cloud properties, (b) improve modeling of NO_x chemistry and air quality forecasting, (c) model carbon fluxes at regional scales and (d) investigate the effects of smoke from pyrocumulonimbus on the stratosphere.

Dust

Satellite observations and ground-based measurements show a positive AOD trend of 0.01–0.04 yr^{-1} over the Middle East region over the period 2003-2012. *Rocha Lima et al.* (2024) investigate if this observed AOD trend was also captured by the NASA Goddard Earth Observing System (GEOS) model. They examine changes in simulated dust emissions and dust AOD during this period, and the results support their hypothesis that the loss of vegetation cover and the associated increase in dust emissions over Syria and Iraq can partially explain the increase in AOD downwind. However, the model simulations indicated dust emissions in the model needed to be 10-fold larger in those grid cells in order to reproduce the observed AOD and trend.

Biomass burning aerosols

Das et al. (2024) use data from a case study to evaluate the aging of biomass burning aerosol coming off southern Africa. They apply a simple loss rate to the model hydrophilic biomass burning organic aerosol to simulate the chemical and microphysical loss processes observed to occur between two plumes of differing ages (4 versus 7 days since emission). They also use ORACLES observations to improve the model representation of aerosol optical properties (particle size, hygroscopic growth, and aerosol absorption). As implemented, these changes improve their simulation for the entire month of September 2016 over the southeast Atlantic region compared to surface-based and satellite-based retrievals. Interestingly, the changes reduce the atmospheric warming over the entire southeast Atlantic region by about 10% (~2 W m^{-2}) compared to their baseline simulation. This is mostly due to decrease in overall aerosol loading as well as the absorption properties of the smoke.

Cirrus cloud properties

Gil-Díaz et al. (2024) conduct a statistical study of cirrus geometrical and optical properties based on 4 years of continuous ground-based lidar measurements with the Barcelona

(Spain) Micro Pulse Lidar (MPL). They use a two-way transmittance method in which the cloud optical depth, the cloud column lidar ratio and the vertical profile of the cloud backscatter coefficient are retrieved without *a priori* assumptions about their optical and/or microphysical properties. The method is illustrated for a cirrus cloud using measurements from the ground-based MPL and from the spaceborne Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). For 203 instances of high-altitude cirrus clouds over nearly four years the mean cloud thickness was 1.8 ± 1.1 km, the mid-cloud temperature -51 ± 8 °C and the linear cloud depolarization ratio 0.32 ± 0.13. The transmittance method yields an average cloud optical depth (COD) of 0.36 ± 0.45 and a mean effective column lidar ratio of 30 ± 19 sr. The highest occurrence of cirrus is observed in spring, and the majority of cirrus clouds are visible ($0.03 < \text{COD} < 0.3$), followed by opaque ($\text{COD} > 0.3$). Together with results from other sites, this study will lead to a better understanding of the properties of cirrus clouds, their spatial distribution, and key processes of formation and evolution. It also will help development of new parameterizations of cirrus clouds to obtain their optical, microphysical and radiative properties and parameterizations of new cirrus cloud products obtained with spaceborne or ground-based lidar instruments.

Air quality forecasting

Acdan et al. (2024) developed a real-time air quality forecasting system using the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) to provide support for flight planning activities during the NOAA Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas (AEROMMA) and NASA Synergistic TEMPO Air Quality Science (STAQS) 2023 field campaigns. This study evaluates the Chicago-centered forecasting forecast skill for a rural area downwind of Chicago that often experiences high levels of ozone pollution. Comparisons to vertical ozone profiles collected by a Tropospheric Ozone Lidar Network (TOLNet) instrument revealed that forecast skill decreases as forecast lead time increases, and comparisons to surface measurements indicate that the forecasting system tended to underestimate ozone concentrations on high ozone and vice versa, regardless of forecast lead time. Wind speed and direction data indicate that this underestimation can partially be attributed to lake breeze simulation errors. Overall, this work helps identify improvements that can be made for future iterations of the WRF-Chem forecasting system.

NOx emissions and chemistry

Hsu et al. (2024) use synthetic TEMPO and TROPOMI NO_2 measurements based on emissions from the COVID-19 lockdown period to investigate the benefit of assimilating high spatial-temporal resolution nitrogen dioxide (NO_2) measurements from a geostationary (GEO) instrument such as TEMPO versus a low-earth orbit (LEO) platform like TROPOMI on the inverse modeling of nitrogen oxides (NO_x) emissions in Observing System Simulation Experiments. They find that NO_x emission biases can be ameliorated using half as many simulation days when assimilating GEO observations, and the estimated NO_x emissions in 23 out of 29 major urban regions in the US are more accurate. Sensitivity experiments demonstrate that the temporal width of the data assimilation window introduces −10% to −20% biases in the emissions inversion and constraining both NO_x concentrations and emissions simultaneously yields the most accurate NO_x emissions estimates. This work serves as a valuable reference on how to appropriately assimilate GEO observations for constraining NO_x emissions in future studies.

Tropospheric ozone is an air pollutant and a greenhouse gas whose anthropogenic production is limited principally by the supply of nitrogen oxides (NO_x) from combustion. Tropospheric ozone in the northern hemisphere has been rising despite the flattening of NO_x emissions in recent decades. *Shah et al.* (2024) propose that this sustained increase could result from the photolysis of nitrate particles ($p NO_3^-$) to regenerate NO_x. Including $p NO_3^-$ photolysis in the GEOS-Chem atmospheric chemistry model improves the consistency with ozone observations. Our simulations show that $p NO_3^-$ concentrations have increased since the 1960s because of rising ammonia and falling SO_2 emissions, augmenting the increase in ozone in the northern extratropics by about 50% to better match the observed ozone trend. $p NO_3^-$ will likely continue to increase through 2050, which would drive a continued increase in ozone even as NO_x emissions decrease. More work is needed to better understand the mechanism and rates of $p NO_3^-$ photolysis.

Lightning-induced NOx

Lightning is one of the primary natural sources of nitric oxide (*NO*), and the influence of lightning-induced *NO* (LNO) emission on air quality has been investigated in the past few decades. *Cheng et al.* (2024) estimate LNO emissions from satellite-observed lightning optical energy, employing it in an air quality modeling system to investigate the potential influence of LNO on tropospheric ozone. Results show that lightning produced 0.174 Tg N of nitrogen oxides ($NO_x = NO + NO_2$) over the contiguous US domain between June and September 2019, accounting for 11.4 % of total NO_x emissions. In August 2019, LNO emission increased ozone concentration within the troposphere by an average of 1 %–2 % (or 0.3–1.5 ppbv), depending on the altitude; the enhancement is maximum at ∼ 4 km above ground level and minimum near the surface. The southeastern US has the most significant ground-level ozone increase, with up to 1 ppbv (or 2 % of the mean observed value) difference for the maximum daily 8 h average (MDA8) ozone. These numbers are near the lower bound of the uncertainty range given in previous studies. The decreasing trend in anthropogenic NO_x emissions over the past 2 decades increases the relative contribution of LNO emissions to total NO_x emission. Performing backward trajectory analyses revealed two main reasons for significant ozone increases: long-distance chemical transport and lightning activity in the upwind direction shortly before the event.

Formaldehyde and volatile organic compounds

Dix et al. (2023) analyze observational and model data to study the sources of formaldehyde over oil and gas production regions and to investigate how these observations may be used to constrain oil and gas volatile organic compound (VOC) emissions. The analysis of aircraft and satellite data consistently found that formaldehyde over oil and gas production regions during spring and summer is mostly formed by the photooxidation of precursor VOCs. Formaldehyde columns over the Permian Basin are correlated with the production locations. Formaldehyde simulations by the atmospheric chemistry and transport model WRF-Chem, which included oil and gas NO_x and VOC emissions from the fuel-based oil and gas inventory, were in very good agreement with TROPOMI satellite measurements. Sensitivity studies illustrated that VOCs released from oil and gas activities are important precursors to formaldehyde, but other sources of VOCs contribute as well and that the formation of secondary formaldehyde is highly sensitive to NO_x. They also investigate the ability of the chemical mechanism used in WRF-Chem to represent formaldehyde formation from oil and gas hydrocarbons by comparing against the Master Chemical Mechanism. Further, their work provides estimates of primary formaldehyde emissions from oil and gas production activities, with per basin averages ranging from 0.07 to 2.2 kg h^{-1} in 2018. A separate estimate for natural gas flaring found that flaring emissions could contribute 5 to 12% to the total primary formaldehyde emissions for the Permian Basin in 2018.

Estimating regional carbon cycles

Atmospheric inversion models have struggled to show skill in solving for net exchange of carbon dioxide between the surface and the atmosphere at sub-continental and seasonal time scales. *Byrne et al.* (2024) developed a new nested version of CMS-Flux for North America (CMS-Flux-NA). They demonstrated the value of this model for studying the regional carbon cycle by solving for a regional, seasonal perturbation in fluxes that occurred due to flooding of the midcontinent of the US during the spring of 2019. This new, one-way nested version of CMS-Flux for North America (CMS-Flux-NA) with high-resolution atmospheric transport over North America solved for reduced CO_2 uptake over the U.S. Midwest during spring 2019 relative to 2018, coinciding with the 2019 Midwest floods. The inversion uses data from OCO-2 and from tower-based *in situ* CO_2 measurements to solve for these fluxes. ACT-America flight data, obtained over this region during this flood event, are used as an independent data to demonstrate the skill of the model. *Byrne et al.* also showed that current data density from OCO-2 cannot constrain regional CO_2 fluxes, but that a daily repeat cycle, possibly from a constellation of LEO satellites would significantly reduce uncertainties.

Modeling the effects of smoke from pyrocumulonimbus on the stratosphere

The Australian mega-wildfires in the austral summer of 2019-2020 injected smoke into the stratosphere. *Ma et al.* (2024) model the smoke plume and reproduce its trajectory toward the middle stratosphere at ~35-kilometer altitude. They use SAGE-III aerosol extinction data of aerosol extinction to validate the model results. They show that a smoke-charged vortex (SCV) induced and maintained by absorbing aerosols played a key role in lofting pollutants from the lower stratosphere and nearly doubled the southern hemispheric aerosol burden in the middle stratosphere. The SCV caused a redistribution of stratospheric aerosols, which boosted heterogeneous chemistry in the middle stratosphere and enhanced ozone production, compensating for up to 70% of the ozone depletion in the lower stratosphere. As global warming continues, we can expect a growing frequency of SCVs due to wildfires with continued impacts on stratospheric aerosols and chemistry.

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 enhanced understanding of the Earth System to improve predictability of tipping points, large-scale climate induced changes, future carbon dynamics and reduction of uncertainty in climate models, and societies and innovative approaches leveraging artificial intelligence and machine learning that will improve the effectiveness of animal species conservation. Ultimately, these results underscore the importance of remote sensing in further understanding interrelating processes across the Earth system, and the role of these data, coupled with models, to predicting changes in Earth's biogeochemistry and biological systems, offering crucial insights for climate science and policy development.

Ocean Biology and Biogeochemistry

The world is working hard to achieve the coveted goal of CO_2 emissions reductions to limit climate change and global temperature rise beyond the 1.5 degrees Celsius threshold. However, research has suggested that, in the coming years, ecosystems and carbon cycle dynamics will change and tipping points may be crossed, creating a world with a lot more uncertainty regarding greenhouse gas sources and sinks. These large-scale, climate induced changes, such as changing ocean chemistry and carbon cycling, can best be observed and put into context utilizing satellite observation, which provide long term, sustained, uninterrupted synoptic measurements of the Earth System. Shutler et al. (2024) underscored the vital role satellites play in not just new and exciting discoveries, but also for ecosystem assessments and carbon budgets. Satellite data are a staple in reports such as the IPCC and the National Climate Assessments, however the authors argue that the full potential of satellite observations to expand the scientific knowledge on critical processes such as the atmosphere-ocean exchange of CO_2 and ocean acidification, including its impact on ocean health, remains largely unexplored, as well as using these observations for guiding ocean management and conservation decisions. The authors go on to identify opportunities and scientific priorities, and ways in which the exploitation and the visibility of satellite observations to policy makers and users can be improved. In a comprehensive review, Schimel and Carroll (2024) point out that robust observations, in particular from remote sensing platforms to complement the paucity and bias of in situ measurements, data-assimilative models, and prediction systems are needed to better understand carbon cycle-climate feedbacks in a world that approaches net zero emissions and how carbon storage will change in the major reservoirs, including the ocean, and what this current uncertainty may mean for future mitigation of climate change.

Terrestrial Ecology

NASA’s Terrestrial Ecology Program continued to support the Arctic-Boreal Vulnerability Experiment (ABoVE), a ten-year field and modeling effort focused on Arctic ecosystems. ABoVE is currently in its last phase (Phase 3, 2022-2026), which focuses on synthesis studies and filling critical research gaps that remain from its previous two phases. Over the duration of ABoVE, our understanding of the changing Arctic-Boreal regions has been significantly improved, in particular the understanding of climate change impacts on greenhouse gas exchange at high latitudes and ecosystem vulnerability to increasing temperatures. ABoVE-funded studies have collectively enhanced our understanding of the carbon cycle by elucidating how disturbances, land cover changes, and permafrost dynamics contribute to greenhouse gas emissions and sequestration. For example, Treat et al. (2024) mapped permafrost carbon stocks and methane seeps across northern terrestrial ecosystems to gain a better understanding of the role of these processes in current and future carbon dynamics. By employing remote sensing techniques, they observed significant methane emissions from permafrost regions, particularly from large sub-permafrost gas seeps. This research highlighted the role of permafrost as a carbon reservoir and its potential contribution to greenhouse gas emissions as it thaws, emphasizing the importance of these emissions in global carbon budgets. Kim et al. (2024) leveraged data from Landsat and the Orbiting Carbon Observatory-2 (OCO-2) to investigate the effects of wildfires on photosynthesis in North American boreal forests. Their study revealed that wildfires initially decrease carbon uptake due to the destruction of vegetation. However, over time, the regeneration of forests with more productive vegetation types leads to increased photosynthesis rates. This finding demonstrated the resilience of boreal forest ecosystems and underscores the complex role of disturbances like wildfires in the carbon cycle. The ability to monitor and predict these changes helps in understanding long-term forest recovery and carbon dynamics. Ramage et al. (2024) combined MODIS and Landsat data to estimate greenhouse gas fluxes in the permafrost region from 2000 to 2020 and gain insights into the net greenhouse gas balance of the permafrost region. The study found that the region is a significant source of methane and nitrous oxide emissions, despite also acting as a carbon dioxide sink. This comprehensive greenhouse gas budget highlighted the significant impact of permafrost thaw on the global greenhouse gas balance. Finally, Engram et al. (2024) used high-resolution satellite data, such as MODIS and Landsat, to create accurate burned-area products and study fire dynamics. They analyzed how different fire regimes affect carbon emissions and forest recovery, providing valuable information for fire management practices. This research is important for predicting the impact of wildfires on the carbon cycle and understanding the long-term effects of fire on forest ecosystems, and emphasizes the value of high-resolution satellite data in effectively monitoring and managing the impacts of wildfires on the carbon cycle.

Land Cover/Land Use Change

Future population growth in mountains is expected mostly in small- and medium-sized cities. Mountain settlements are often omitted from global land cover analyses due to the low spatial resolution of satellite images. The study by Chen et al., (2023) demonstrates the potential of deep learning to detect human settlements in mountains at the sub-pixel level using Landsat imagery. For spatial features, the authors compared a U-shaped neural network (U-Net) with a random forest (RF) algorithm. Temporal features were assessed using multispectral imagery and the Continuous Change Detection and Classification (CCDC) algorithm. The U-Net outperformed the RF in mapping small settlements and captured long-term urban growth. The study revealed that the built-up area in the Hindu Kush Himalaya expanded by 61 km^2 per year from 1990 to 2020, double the estimate from the Global Human Settlement Layer and highlights the potential of deep learning algorithms in mapping human settlements at a sub-pixel scale.

Biodiversity and Ecological Conservation

The BioSCape campaign, conducted in fall 2023, collected extensive biodiversity field data, including vegetation surveys, water quality data, environmental DNA (eDNA) surveys, acoustic recordings, and terrestrial lidar scans in concert with airborne measurements. The project emphasized inclusivity by fostering collaborations with South African researchers, incorporating local expertise, and ensuring transparent decision-making. Outreach efforts featured community events, educational programs, and capacity-building workshops, while ethical participation and conflict resolution were prioritized through pre-field training and a comprehensive Code of Conduct. By the end of 2024, BioSCape aims to understand stakeholder priorities, solidify the BioSCape Community of Practice, and further high-value applications through end-user engagement. Progress has been driven by the May 2023 Applications workshop, which identified key decision-making needs. A proposed 2025 workshop will further showcase BioSCape data products and strengthen international collaborations. Ongoing activities include regular communication between the BioSCape Science Team and South African stakeholders, organizing workshops, and participating in regional networks to maximize the use of BioSCape and NASA data in decision-making processes in South Africa. BioSCape is paving the ground towards co-production of knowledge to enhance and improve predictive capabilities of how the Earth System is interconnected and changing.

Kays and Wikelski (2023) developed a new concept called the Internet of Animals (IoA) that represents a unique way of thinking about how to understand global biodiversity by extending digital knowledge and infrastructure to animal life. This new paradigm integrates comprehensive data sets on animals worldwide, offering novel insights into their needs and behaviors while guiding sustainable human-wildlife coexistence. As the IoA evolves, it contributes valuable information for forecasting ecological conditions and improving conservation strategies. However, unlocking IoA's full potential requires addressing challenges such as taxonomy standardization, data security, and effective data sharing. By integrating datasets, updating in real-time, and automating workflows, IoA has the potential to drive critical discoveries and predictions crucial for human societies and the conservation of animal species. Although still developing, the IoA framework enhances our ability to predict and address environmental challenges by incorporating diverse sources of information.

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.

Cryosphere in the Climate System

Sea Ice

Winds blew a record large portion of the Arctic's multiyear sea ice into the southern Beaufort Sea in winter 2021. From early March, a network of buoys from the Sea Ice Dynamic Experiment (SIDEx) tracked the MYI as it drifted across the southern Beaufort Sea toward the Chukchi Sea. Transport was episodic as the consolidated ice pack interacted with coastal boundaries and repeatedly fractured. *Jewell et al. (2024)* investigated variability in 2021 multiyear sea ice transport by relating in situ sea ice drift to remotely sensed coastal lead opening events, which have been shown to increase ice drift speeds in winter. Daily ice concentration data show ten opening events occurred throughout March and April 2021. These openings lasted 1–5 days as southeasterly winds pushed the southern Beaufort Sea ice pack away from local coastal boundaries. During opening, the ice pack abruptly accelerated and its response to wind forcing stabilized around free drift conditions. With this efficient wind-to-ice momentum transfer, nearly all (94%) southern Beaufort Sea multiyear sea ice transport in March–April 2021 occurred during opening events, despite spanning just half the time. Only 6% of transport occurred during the other half of days without opening. On these days, the ice was mostly as northwesterly winds compressed the pack against the coast. Spatiotemporal discontinuities in ice-wind speed ratios were measured across several coastal leads that transected the SIDEx buoy network, providing direct observations of ice drift modulation by coastal lead formation. These results quantify the disproportionate contribution of coastal lead opening events to southern Beaufort Sea ice transport during spring 2021, highlighting the critical role these transient events play in patterns of sea ice drift at seasonal timescales.

Land Ice

Warm water from the Southern Ocean has a dominant impact on the evolution of Antarctic glaciers and in turn on their contribution to sea level rise. Using a continuous time series of daily-repeat satellite synthetic-aperture radar interferometry data from the ICEYE constellation collected in March–June 2023, *Rignot et al. (2024)* documented an ice grounding zone, or region of tidally controlled migration of the transition boundary between grounded ice and ice afloat in the ocean, at the main trunk of Thwaites Glacier, West Antarctica, a strong contributor to sea level rise with an ice volume equivalent to a 0.6-m global sea level rise. They presented evidence for seawater intrusions occurring at tidal frequencies over many kilometers beneath the grounded ice of Thwaites Glacier, West Antarctica, a major contributor to sea level rise. The results call into question the traditional approach of modeling a fixed, abrupt transition from grounded ice to ice floating in the ocean with no ice melt at the transition boundary. They delineated a tidally controlled grounding zone, 2 to 6 kilometers in length, and additionally irregular seawater intrusions extending another 6 kilometers inland at spring tide. The rushing of seawater beneath grounded ice over considerable distances makes the glacier more vulnerable to melting from a warmer ocean than anticipated, which in turn will increase projections of ice mass loss.

Determining reliable probability distributions for ice sheet mass change over the coming century is critical to refining uncertainties in sea-level rise projections. Bayesian calibration, a method for constraining projection uncertainty using observations, has been previously applied to ice sheet projections but the impact of the chosen observation type on the calibrated posterior probability distributions has not been quantified. *Felikson et al. (2023)* used three separate Bayesian calibrations to constrain uncertainty in Greenland Ice Sheet (GrIS) simulations of the committed mass loss in 2100 under the current climate, using observations of velocity change, dynamic ice thickness change, and mass change. Comparing the posterior probability distributions shows that the median ice sheet mass change can differ by 119 % for the model ensemble that was used, depending on the observation type used in the calibration. More importantly for risk-averse sea-level planning, posterior probabilities of high-end mass change scenarios are highly sensitive to the observation selected for calibration. They showed that using mass change observations alone may result in model simulations that overestimate flow acceleration and underestimate dynamic thinning around the margin of the ice sheet.

The Pine Island and Thwaites glaciers are the two largest contributors to sea level rise from Antarctica. *Joughin et al. (2024)* examined the influence of basal friction and ice shelf basal melt in determining projected losses. The ice sheet simulations used in this study were performed using the Ice-sheet and Sea-level System Model (ISSM). The simulations are initialized to the year 2007 by inverting for a basal friction coefficient field using surface topography from the Greenland Ice Mapping Project (GIMP), bed topography from BedMachine v3, and surface velocity from Interferometric Synthetic Aperture Radar (InSAR) satellite data. They examined both Weertman and Coulomb friction laws with explicit weakening as the ice thins to flotation, which many friction laws include implicitly via the effective pressure. The study found relatively small differences with the choice of friction law (Weertman or Coulomb) but find losses to be highly sensitive to the rate at which the basal traction is reduced as the area upstream of the grounding line thins. Consistent with earlier work on Pine Island Glacier, they found sea level contributions from both glaciers to vary linearly with the melt volume averaged over time and space, with little influence from the spatial or temporal distribution of melt. Based on recent estimates of melt from other studies, these simulations suggest that the combined melt-driven and sea level rise contribution from both glaciers may not exceed 10 centimeters by 2200, although the uncertainty in model parameters allows for larger increases.

<u>Oceans in the Climate System</u>

Estimating the Circulation and Climate of the Oceans

The ECCO model and assimilation system have been used in many applications, from globally averaged heat content to help interpret high resolution SWOT data. The ECCO project estimates Ocean Heat Content by assimilating in-situ and satellite data into the MIT numerical ocean model. Their estimate of full depth, total heat absorbed in 2023 is 16 ZJ, or approximately 154 times the global electricity production for 2023.

Observations since 2008 reveal pronounced regional acceleration of sea level rise in the Gulf of Mexico. ECCO and observational data were used to find that subsurface ocean warming has caused mass redistribution within the Gulf of Mexico leading to positive coastal sea-level trends (*Steinberg et al 2024*). *Wang et al (2023)* use NASA's observation-constrained ECCO ocean state estimate and adjoint sensitivity analysis to conclude that offshore winds impact Charleston's sea level variations significantly more than Nantucket's, leading to their sea level incoherence.

The SWOT mission is yielding sea surface height at spatial resolutions of order 1-10 km. At these short scales, the geostrophic approximation that allows to compute ocean surface current from nadir altimetry sea surface height is no longer valid. These difficulties are solved by estimating the joint probability density functions of surface vorticity, strain magnitude, and divergence, rather than the current velocities (*Xiao et al 2023*). A high resolution version of ECCO is used to train and verify a neural network to estimate these properties. They show that these statistical properties of the flow allow identification of the flow signatures of submesoscale vortices and fronts and the presence of internal gravity waves.

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

Coastal flooding, one of the major threats to nearshore regions, has increased along the U.S. East Coast in recent decades. Atmospheric pressure and river runoff have the most influence on sea level anomalies over short time scales, while over long time scales remote forcing has the strongest influence (*Zhu et al 2024*). Remote forcing includes variability in the Gulf Stream, basin-scale wind stress, and oceanic signals entering the region from the North and East. *Volkov et al (2023)* show that AMOC-induced changes in gyre-scale heat content, superimposed on the global mean sea level rise, are already influencing the frequency of floods along the United States southeastern seaboard, with gyre-scale warming accounting for 30-50% of flood days in 2015-2020.

Flooding hazard in a coast is due both to rising seas and falling land, commonly referred to as vertical land motion. *Buzzanga et al (2023)* used satellite radar and in-situ GPS data to estimate the rates of vertical land motion of the densely populated New York City metropolitan area at 30m resolution; they found subsidence (falling land) at 1 inch in approx. 16 years. These results will inform efforts to adapt to the flooding hazard.

Many coastlines lack accurate long-term sea level observations, needed to project future changes. *Dangendorf et al (2024)* introduce a novel probabilistic near-global reconstruction of sea-level changes relative to the coast and their causes over the period 1900 to 2021. The reconstruction is based on tide gauge records and incorporates prior knowledge about physical processes from ancillary observations and geophysical model outputs. It demonstrates very good agreement between the reconstruction and satellite altimetry and tide gauges.

Integrated Earth System & Modeling

At shorter time scales, the IESM-supported NASA Goddard Earth Observing System (GEOS) provides a global, near-real time weather analysis and forecast products. Reichle et al. [2023] introduced a land analysis into the GEOS Hybrid-4DEnVar system to additionally assimilate L-band (1.4 GHz) brightness temperature observations over land from the NASA Soil Moisture Active Passive (SMAP) satellite mission, which are highly sensitive to surface (~0-5 cm) soil moisture. This weakly-coupled land analysis impacts the simulated and forecast atmosphere through the land-atmosphere exchange processes encoded in the atmospheric model. The SMAP assimilation is shown to mitigate errors in 2-m specific humidity and temperature, with regional reductions in the root mean square error (RMSE) of q2m and maximum daily T2m by up to 0.4 g kg-1 and 0.3 K, respectively. Forecasts of q2m and T2m have significantly improved anomaly correlation and RMSE (99% confidence) at lead times out to 5 days compared to the system without SMAP assimilation, demonstrating the importance of an integrated, Earth system approach to prediction.

Soil moisture also plays an important role in heat waves, and soil moisture thresholds affect heatwave predictability and the role of land-atmosphere coupling. Benson and Dirmeyer [2023] evaluates forecast models from the Subseasonal Experiment (SubX) (in which the NASA GEOS-S2S modeling system participates), and the NOAA Unified Forecast System (UFS) by comparing them against reanalysis data. Findings indicate that while models struggle to initialize correctly at soil moisture breakpoints, they improve when adjusted for soil moisture climatology deficiencies. Performance varies regionally, being better in the Northwest US than in the Southwest. Models predict extreme heat well initially but struggle with soil moisture feedback. Forecast models generally perform better at extreme heat prediction when they are already dry and in the hypersensitive regime. The study suggests that improved soil moisture initialization could enhance extreme heat forecasts.

An important research priority for IESM is the evaluation and simulation of wildfire extremes. Wildfires pose increasing risks to human health in North America. Large uncertainties in fire emission, transport, and chemical transformation complicate accurate air quality prediction during wildfire events. Li et al. [2024] presents a new real-time Hazardous Air Quality Ensemble System (HAQES) by leveraging various wildfire smoke forecasts from three U.S. federal agencies (NOAA, NASA, and Navy). The HAQES ensemble forecast significantly enhances accuracy. Additionally, a weighted ensemble forecast approach reduced fractional bias by 34% in the major fire regions, false alarm rate by 72%, and increased hit rate by 17%. Further improvements were obtained by using quantile regression and weighted regression methods to forecasting extreme air quality events. The advanced weighted ensemble increased the $PM_{2.5}$ exceedance hit rate by 55%. The findings demonstrate a practical way to enhance decision-making support to protect public health.

At subseasonal to seasonal time scales, Atmospheric Rivers can produce extreme events. Schubert et al. [2023] used NASA GEOS Atmospheric Global Climate Model and a stationary wave model to investigate the causes and predictability of the unprecedented series atmospheric rivers (ARs) which hit California during the winter of '22/'23, focusing on remote forcing regions, mechanisms, and underlying predictability of this flooding event. It revealed the underlying causes of the persistent positive Pacific–North American (PNA)-like circulation pattern that caused the development of the ARs. The pattern was due to vorticity forcing in the North Pacific jet exit region which was caused by an MJO-forced Rossby wave that propagated from the northern Indian Ocean into the North Pacific. The study unfortunately found a fundamental lack of predictability of the event at seasonal time scales. Forecasts suggest that useful skill in predicting the PNA and extreme precipitation over California is limited to lead times shorter than about 3 weeks.

Prediction of tropical cyclone systems is another seasonal prediction priority. Garcia-Franco et al. [2023] evaluates the representation of tropical cyclone precipitation (TCP) in reforecasts from the Subseasonal to Seasonal (S2S) Prediction Project in which NASA is involved, established by the World Weather Research Program (WWRP) and the World Climate Research Program (WCRP). The global distribution of precipitation in S2S models shows relevant biases in the multimodel mean ensemble that are characterized by wet biases in total precipitation and TCP, except for the Atlantic. The TCP biases can contribute more than 50% of the total precipitation biases in basins such as the southern Indian Ocean and South Pacific. The TCP biases result from biases in the frequency of tropical cyclone occurrence - too few TCs in the Atlantic and western North Pacific and too many TCs in the Southern Hemisphere and eastern North Pacific. At the storm scale, the average peak precipitation near the storm center is lower in the models than observations due to a too high proportion of weak TCs. The study suggests that the simulation of TC occurrence and the storm-scale precipitation requires better representation in order to reduce TCP biases and enhance the subseasonal prediction skill of mean and extreme total precipitation.

The impact of improved ocean-atmosphere coupling in Earth system models on prediction is being investigated within IESM. Numerous scientists funded by the CVC focus area were involved in the production of a new CLIVAR report published in August, 2023 [Clayson et al. 2023], focused on improving prediction skill through improved observations and modeling of air-sea interaction in the air-sea transition zone (ASTZ). The multiagency ASTZ Study Group released the report which recommends four strategies to advance observing and modeling capabilities and understanding of air-sea interaction at all required scales for ESP: develop observational and modeling technology for coupled ocean-atmosphere prediction, observe the ASTZ in strategic regions, expand observations of extremes and other challenging regimes, and develop a global observing network to monitor key air-sea coupling variables.

<u>Section 1.1.9.4</u> Earth Surface and Interior Focus Area

NASA's Earth Surface and Interior focus area (ESI) supports research aimed at characterizing the dynamics of the solid Earth, improving the capability to assess and respond to natural hazards and extreme events. Building on the body of work under 1.1.8 "characterizing the behavior of the Earth system," ESI studies seek to improve understanding of the interacting processes that "control the behavior of the Earth system" and hence "improve predictive capability" as described under performance goal 1.1.9. Improving predictive capability in ESI centers on working towards probabilistic forecasting, since the prediction of place, time, and intensity of an event in the solid-Earth system is generally not yet possible. With this in mind, studies that inform, or develop capabilities to help inform the occurrence of future events or the effects they may have on a larger system are classified under 1.1.9. In 2024 ESI observed an increase in publications attempting to quantitatively identify features and processes that can be linked to an increased likelihood of an event occurring. By better understanding how these features and processes can be detected and how they link to the event being studied, ESI takes a step closer to being able to quantitatively forecast these events.

Geohazards

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

Earthquakes

Identifying the methods for monitoring and measuring earthquakes and the seismic cycle are useful in mitigating and forecasting future events. One commonly-used method of evaluating the future earthquake potential of a known fault is to estimate the moment rate accumulating along that fault. In other words, by determining the seismic moment it can be estimated how much earthquake energy is accumulating over time. Guns et al., (2024) used GNSS velocity data in conjunction with Kostrov thickness values that were calibrated from three published fault-based models of Southern California to partition moment rate into on-fault and off-fault moment rate. Their results suggest that including uncertainties in Kostrov thickness brings fault-based geodetic moment rate closer to the seismic moment release. This will provide researchers a more robust understanding of uncertainty bounds for seismic moment accumulation rate.

Volcanoes

Understanding the processes that lead to an eruption helps 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. Acocella et al., (2024 – Nature) explored first-order scientific approaches using different monitoring techniques that are essential to progress towards forecasting the time and location of magmatic eruptions. The authors found that the use of physics-based models to assimilate monitoring data and observations can substantially improve forecasting but requires a deeper understanding of pre-eruptive processes and more extensive monitoring data.

Ramsey et al., (2023) provided a statistical retrieval from two decades of ASTER data to constrain volcanic activity patterns throughout pre- and post-eruption phases with a focus on subtle (1−2 K) thermal behavior, which is easily overlooked using lower spatial resolution data. The new statistical algorithm automatically detected the full range of thermal activity and applied it to >5000 ASTER scenes at five volcanoes with well-documented eruptions. The authors found that smaller, subtle thermal detections served as precursory signals in ∼81% of eruptions. The algorithm's results have the potential to create a framework for classifying future eruptive styles.

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. Li et al., (2024 – GRL and LA Times) used InSAR and pixel tracking of PlanetScope optical data to characterize the precursory motion of a catastrophic landslide. They found that the slow, progressive, accelerating deformation that precedes catastrophic landslides differs from the persistent motion of slow-moving landslides, which can be distinguished by analyzing their time-dependent motion. The authors state that this work highlights the importance of monitoring incipient slow motion of landslides, particularly where no discernible historical displacement has been observed to better forecast larger landslides.

Section 1.1.9.5 Water and energy Cycle Focus Area

NASA's Water and Energy Cycle focus area (WEC) supports several NASA modeling systems that facilitate progress towards enhanced understanding of the Earth System, its predictability, and of opportunities for enhanced prediction. An important goal of the WEC is continued development of fully-coupled Earth System models with improved representation of land-atmosphere processes, land-atmosphere-ocean feedbacks, and their sensitivity to climate variability. In this section, NASA Land Data Assimilation System (LDAS) and Goddard Earth Observing System model (GEOS) physics-based modeling activities, along with emerging machine learning applications are highlighted.

A longstanding Internal Scientist Funding Model work package award to GSFC supports the maintenance and continued technical development of NASA's LDAS. LDAS comprises two near real-time implementations of the Land Information System (LIS): the 1-hourly and 1/8th degree resolution North American Land Data Assimilation System (NLDAS) and the 3-hourly and 1/4th degree resolution Global Land Data Assimilation System (GLDAS). Data products from both NLDAS and GLDAS are delivered to the NASA GES-DISC for public dissemination. Model outputs include soil moisture, soil temperature, surface sensible and latent heat fluxes, and surface and subsurface runoff. NLDAS and GLDAS serve large domestic and international user communities, including through the US Drought Monitor (https://droughtmonitor.unl.edu/) and the US Agency for International Development Famine Early Warning Systems Network (https://fews.net/).

LDAS outputs commonly serve as initial conditions for weather, climate, and water supply prediction models. Significantly, LIS is implemented as part of NOAA's operational Climate Forecast System to provide daily initial land states. Over a range of sub-daily to subseasonal-to-seasonal timescales and environmental conditions, forecast skills of: soil moisture, air temperature, daytime planetary boundary layer height, precipitation, streamflow, mesoscale circulations, and circumglobal teleconnections have each been shown to correlate with initial soil moisture state accuracy. Accordingly, LDAS realism can be a driving factor in potential prediction skill of weather and hydrologic forecast models.

Since 2015, LIS has been open source with a public repository hosted on GitHub (https://github.com/NASA-LIS/LISF). Experimental LIS configurations are commonly developed and applied with support from NASA ESD competed research funding to address specific scientific hypotheses or stakeholder needs, but with a common goal of improving both accuracy and physical realism of the LDAS. Such projects have tended to explore one of more of the following themes: sensitivity to inputs – either meteorological forcing or soil and vegetation datasets; single and multi-parameter calibration; expansion of process representation (e.g., irrigation, tile drainage, nutrient limitations, snow albedo, root-groundwater interactions); improvement of process representation (e.g., addition of snow and soil layers, refinement of groundwater representation); and assimilation of additional satellite and in-situ data. For example, Navari et al. (2024) improve LIS estimates of snow depth and snow water equivalent by coupling the detailed snow model, Crocus to LIS. Another excellent example is Maina et al. (2024). They develop and apply a new LIS implementation in the production of a state-of-the-art 5 km and daily resolution land reanalysis for High Mountain Asia that spans the period from 2003–2020. This land reanalysis integrates best-estimate meteorological forcings and multivariate assimilation of: GRACE terrestrial water storage, SMAP soil moisture, MODIS leaf area index, MODIS snow cover fraction, and regional irrigation estimates. Relative to a parallel no-data assimilation or so-called "open-loop" LIS simulation, the full reanalysis with land data assimilation is shown to more accurately represent both seasonal streamflow variability and long-term regional declines in streamflow. The authors explain that the land data assimilation captures irrigation-driven groundwater depletion and associated greening, as well as corrects model process representation deficiencies including those of snow and vegetation dynamics. The reanalysis provides spatially and temporally consistent estimates of storages, fluxes, and meteorological conditions including snow (depth, water equivalent), skin/snow/ice temperature, soil moisture, evapotranspiration, groundwater storage, and streamflow that are relevant for a range of hydroclimate investigations and societal applications. The dataset is publicly available and archived at the National Snow and Ice Data center (NSIDC, https://nsidc.org/data/hma2_nlsmr/versions/1) Distributed Active Archive Center (DAAC). Several additional LIS research implementations have been highlighted in response to Annual Performance Goal 1.1.8. The lessons learned from LIS research implementations form the basis for future upgrades to the version of LIS implemented in NLDAS and GLDAS operational systems.

NASA ESD also supports GEOS seasonal forecast model development and applications. GEOS is used to produce the NASA global atmospheric reanalysis (MERRA-2) as well as quasi-operational S2S forecasts that are contributed to the ongoing North American Multi-Model Ensemble, an interagency/intergovernmental ensemble of coupled models from centers in the US and Canada (https://www.ncei.noaa.gov/data/north-american-multi-model-ensemble/access/). Within the hydrometeorological prediction community, the damaging floods in California from December 2022–January 2023 have provided a new focal point for investigation. During this period, California experienced a historic run of nine consecutive landfalling atmospheric rivers. To identify the remote forcing regions, mechanisms and underlying predictability of this event, Schubert et al. (2024) employ GEOS in a "replay" mode, together with more idealized simulations with a stationary wave model. They conclude that predictability of the flooding is contingent on the predictability of two precursor events: the mid-December forcing of the Indian Ocean short wave by the Madden-Julian Oscillation and the late-December forcing of the positive Pacific-North American pattern by the mature Indian Ocean short wave. Forecasts initialized well before mid-December have no skill due to the limited (i.e., 1-month) predictability of the Madden-Julian Oscillation. In a study of the same event, but with output from the fully-coupled GEOS, Deflorio et al. (2024), concluded similarly: forecasts initialized prior to December 17 have little predictive skill. Understanding predictability as a function of lead time is critical to both interpreting model prediction statistics and identifying opportunities for continued model improvement (i.e., as per previously WEC funded Mariotti et al. 2020).

Statistical and machine learning/AI approaches to prediction are also an important part of the NASA ESD research portfolio. Crow et al. (2024) point to the strong relationship between late-fall soil moisture and springtime streamflow in mid-scale U.S. river basins as a key source of potential seasonal hydrologic predictability. Using SMAP (top) 0–1 m soil moisture and USGS streamflow, they evaluate the NOAA National Water Model's ability to accurately represent soil moisture auto-correlation and coupling with streamflow. Their findings reveal that the National Water Model underestimates both trans-winter soil moisture memory and correlation between 0 -1 m soil moisture and streamflow—thereby effectively limiting the model's long-term stream flow forecasting skill.

Rateb et al. (2024) demonstrate the utility of GRACE TWS for flood forecasting applications. They report detectable antecedent GRACE TWS anomalies 15–50 days prior to a subset of floods caused by persistent rainfall, monsoonal patterns, snowmelt, and rain-on-snow events. This finding, they suggest, highlights the broader value of GRACE TWS for post-flood impact and recovery assessments.

Fleming et al. (2024) evaluated NASA's spatially and temporally complete MODIS Snow Covered Area and Grain-size fractional snow-covered area dataset (STC-MODSCAG) as input to current and proposed Natural Resources Conservation Service operational US West-Water Supply Forecast (WSF) systems. Whereas the current WSF system is based on principal component regression (PCR), the future release candidate WSF system is built on a multi-model machine learning metasystem (M4). M4 comprises six semi-independent forecast systems, each built around a different supervised learning algorithm. It integrates statistical pattern recognition; multi-model ensembles; explainable-, physics-constrained, and automated AI; genetic algorithm-based feature selection; non-Gaussian and heteroscedastic prediction uncertainty estimation; parsimonious AI implementations to minimize degrees of freedom and optimize data set length requirements for parameter training; and parallel computation. Added-value of STC-MODSCAG data in specifically quantified for: short lead-time forecasts, issued late in the forecast season; longer lead-time forecasts issued mid-season; and long lead-time forecasts issued early in the season. The results show that STC-MODSCAG data substantially improve long-lead/early-season (i.e., January) forecasts in M4 for all four of the California basins studied. M4 yielded clear benefits over the conventional PCR-based WSF and in some cases leveraged the STC-MODSCAG data more effectively. The authors suggest that machine learning will play a critical role in multi-sensor satellite snow depth and SWE products and successful water management going forward.

Lastly, Lorenz et al. (2024) quantify the effect of machine learning methods on statistical–dynamical forecasts of soil moisture and a satellite-based evaporative stress index (ESI) on subseasonal time scales (i.e., 15–28 days). Model predictors include the current and past land surface conditions and ECMWF dynamical model hindcasts from the World Weather Research Programme/World Climate Research Programme Subseasonal to Seasonal Prediction project (Vitart et al. 2017). Gradient boosting machine and artificial neural network methods are shown to outperform random forest, multivariate adaptive regression spline, generalized additive models, and support vector machine methods. For soil moisture, the best machine learning methods perform only slightly more skillfully than linear methods. Most forecast improvements derive from soil moistening rather than soil drying (i.e., drought recovery). For ESI, the linear methods are still as good or better, which may be due to greater noise in the satellite-based ESI timeseries relative to model-based soil moisture. Increases in skill for both soil moisture and ESI are almost exclusively attributed to predictors drawn from observations of current and past land surface states, which underscores the need for continued refinement of NASA’s LDAS.

Section 1.1.9.6 Weather and Atmospheric Dynamics Focus Area

For demonstrating progress in enhancing understanding of the interacting processes that control the behavior of the Earth system, and in utilizing the enhanced knowledge to improve predictive capability, Weather and Atmospheric Dynamics (WAD) invests in understanding precipitation processes, atmospheric dynamics, extreme events including lightning, convective processes, and heuristic atmospheric analysis. In addition, WAD helps improve forecasts through research on numerical weather prediction, modeling, and data assimilation systems.

Recent investments supported the development of the NASA-NOAA-DOD Joint Effort for Data Assimilation Integration (JEDI), which is led by the Joint Center for Satellite Data Assimilation (JCSDA). Using generic programming and object-oriented design, JEDI develops efficient, flexible, and user-friendly scientific software with the aim to create an integrated data assimilation system for the modern era. JEDI is accepted by NOAA and the Navy as the next generation data framework for weather forecasting. It is also increasingly prototyped by NASA and NOAA for coupled ocean-atmosphere models for subseasonal to seasonal prediction systems. The joint data assimilation and prediction framework streamlines the weather and short-term climate prediction workflow, which benefits the public by providing timely and skillful weather predictions and climate projections.

Significant progress was measured via peer-reviewed publications during the evaluation period and other metrics such as code releases and community engagement pertaining to JEDI. For brevity, select progress related to understanding of the Earth system, with linkages to improved predictive capabilities, are summarized in the following subsections.

Development and Application of Data Assimilation Systems

JEDI Development, Testing, and Releases: The JCSDA spearheads the JEDI project, which aims to develop a modern, integrated data assimilation system. NASA is heavily involved in JEDI to improve data assimilation for its Global Earth Observing System (GEOS) model, ensuring scalability for future initiatives like coupled Earth system data assimilation. JCSDA provides regular roll-up software releases via an integrated end-to-end ecosystem named JEDI-SKYLAB, which are cloud containers that can be used for PI-level development. Updated JEDI-SKYLAB capabilities are available for the atmosphere, ocean, sea-ice, soil moisture, snow, aerosols, and composition.

JEDI-SKYLAB 8.0 was released in April 2024 and introduced significant enhancements, including the addition of multi-radar multi-sensor, ground-based radar (Park et al. 2023), visible reflectance from the Advanced Baseline Imager (ABI) on Geostationary Operational Environmental Satellites (GOES) 16-18, and surface soil moisture from the Soil Moisture Active Passive (SMAP) sensor for land experiments. The marine component also saw increased efficiency and the removal of outdated code, and the trace gas experiment gained ensemble four-dimensional variational (4DEnVar) capability and improved horizontal localization. These upgrades improved data assimilation accuracy and efficiency across the system. Other JEDI-SKYLAB 8.0 updates have significant community impacts including compatibility with cloud or high-performance systems such as Amazon Web Services, NASA Discover, National Center for Atmospheric Research (NCAR) Derecho, and NOAA ParallelWorks, among others.

JEDI Algorithmic Development and System Hardening: Recent updates have greatly enhanced the transition process from the Gridpoint Statistical Interpolation (GSI) analysis to JEDI. In close collaboration with the NASA Global Modeling and Assimilation Office (GMAO), two major corrections were implemented. The first resolved halo handling issues and data synchronization, improving the reproducibility and accuracy of results. The second correction involved enhancing 4DEnVar with GSI background error covariance in JEDI, paving the way for direct cycling comparisons. Work was also undertaken to integrate tracers into the Finite-Volume Cubed-Sphere Dynamical Core (FV3)-linear forecast model, enabling atmospheric composition 4D Variational data Assimilation (4DVar) using tangent linear and adjoint code. Significant effort has also been dedicated to cycling JEDI with the GEOS-Composition Forecast (GEOS-CF) model using 4DVar and 4DEnVar, and assessing their stability for trace gas and aerosol applications.

Aerosol Data Assimilation: Aerosol assimilation was improved with Community Radiative Transfer Model (CRTM) aerosol optical depth using NASA lookup tables and a generalized aerosol lookup table loader for optical properties was developed within the CRTM code. This allows users to create their own aerosol schemes and optical coefficients, thereby increasing the flexibility of CRTM for aerosol assimilation. In addition, significant developments in JEDI have enabled aerosol variable transforms for particulate matter surface observations. Work has also begun to enhance variable change in JEDI, allowing users to adjust their aerosol state to match specific aerosol lookup tables. This enhances the transferability and comparability of interagency efforts in aerosol data assimilation (Wei et al. 2024). Research is ongoing to develop scene classification methods to differentiate between cloud and aerosol-contaminated pixels.

Data Assimilation of Tropospheric Emissions: Monitoring of Pollution (TEMPO) Observations: A significant priority was placed on the JEDI code's capability to assimilate data from TEMPO. Within 24 hours of the official Level 2 public release, news articles were published showcasing data assimilation results of NO_2 fields using TEMPO, highlighting JEDI's operational readiness.

Sea-ice, Ocean, and Coupled Assimilation: Marine data assimilation, focusing on ocean and sea-ice components, is being prepared for integration into NASA and NOAA's next-generation systems (Zhu et al. 2024). In collaboration with GMAO, this assimilation is also used to initialize the ocean and sea-ice models for the upcoming GEOS upgrade. Using JEDI provides access to a wide range of data assimilation methods (Frolov et al. 2024). The project includes advancements in coupled data assimilation, where the ocean and atmosphere are used as backgrounds for ocean surface-sensitive radiances. These radiance observations include sea surface temperature (SST) sensitive infrared (IR) and microwave satellite observations that are simulated via JCSDA's CRTM (Johnson et al. 2023).

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

Convective Processes Experiment – Cabo Verde (CPEX-CV): CPEX-CV was a NASA field campaign that took place in September 2022 using the NASA DC-8 out of Sal Island, Cabo Verde. CPEX-CV investigated the process-level interactions between atmospheric dynamics, marine boundary layer properties, convection, and the dust-laden Saharan Air Layer across various spatiotemporal scales over the data-sparse eastern tropical North Atlantic. CPEX-CV included a cutting-edge payload that utilized a suite of active, passive, and in situ sensors to perform 13 research flights that totaled over 90 hours and released over 400 dropsondes to measure the evolution of atmospheric dynamics, thermodynamics, composition, and microphysics. CPEX-CV also collaborated with the European Space Agency (ESA) to perform several underpasses of ESA's Aeolus Explorer wind lidar and coordinated efforts to overpass ESA partner ground-based sites and aircraft. Campaign data was made publicly available on NASA's Atmospheric Science Data Center (ASDC) and Global Hydrometeorology Resource Center (GHRC) in April 2023.

There have been over 60 presentations at conferences, two MS theses with several MS and PhD dissertations in progress, and nine journal articles that have utilized CPEX – Aerosols & Winds (CPEX-AW) and/or CPEX-CV data. Nowottnick et al. (2024) recently provided an overview of the CPEX-CV campaign and highlights flights from the various CPEX-CV science objectives. Wu et al. (2024) investigated the role of Mesoscale Convective System (MCS) contributions to western Africa rainfall and found that off-shore convection is more frequently generated from off-shore environmental conditions rather than westward propagating MCSs that originally developed over land. Rodenkirch and Rowe (2024) investigated impacts of near-storm environmental conditions on tropical oceanic convection and found larger thunderstorms are linked to greater moisture and wind shear in the lower and middle troposphere. Additional CPEX-CV analysis is ongoing and is expected to yield several additional relevant publications.

Regarding three-dimensional wind retrievals, Borne et al. (2024) used radiosonde launches from CPEX-AW to validate Level 2B wind profiles from ESA's Aeolus-Explorer instrument. They concluded that Rayleigh-clear winds do not meet the Aeolus mission's random error requirement, while Mie winds most likely do not fulfil the mission bias requirement. Additional degradation was observed below clouds or within dust layers, providing valuable information to improve retrieval algorithms using Doppler wind lidar.

Improved Prediction of Tropical Storm Origins, Track, Intensity, and Flooding

Representation of African Easterly Waves in GEOS: African easterly waves (AEWs) exert significant influence on local and downstream high-impact weather including tropical cyclone (TC) genesis over the Atlantic. Accurate representation of AEWs in climate and weather prediction models therefore is necessary for skillful predictions. Jiang et al. (2023) examined simulated AEWs in the NASA GEOS-5 atmospheric global model and used Atmospheric IR Sounder (AIRS) Version 6 Level 3 temperature and specific humidity data to evaluate how well AEWs are simulated in the model. The observed westward propagating AEWs along the Atlantic southern track were largely captured in GEOS-5, but with a slower phase speed and significantly weaker amplitude downstream off the West Africa coast. The weak downstream development is accompanied by much reduced TC genesis over the main development region. Further analyses suggest that the slow westward propagation and weaker AEW amplitude can be ascribed to a weak African easterly jet, providing feedback for potential improvements and iterations to the GEOS-5 model.

Improving the Representation of TCs in Global Analyses and Forecasts: Progress was made on assimilating IR hyperspectral radiances in the presence of clouds, with the goal of improving TC representations in global analyses and forecasts. One improvement was the use of a machine learning adaptive methodology that recognizes TCs from geostationary imagery (Reale et al. 2023). Another was in establishing the foundation of all-sky IR radiances assimilation (i.e., including radiances from cloudy areas). The cloud-detection scheme in the GEOS model was removed, six water vapor channels were selected, and the framework for all-sky assimilation of Cross Track IR Sounder (CrIS) - full spectral resolution data was tested. The modifications increased the number of assimilated observations in the lowest-peaking channel. Results were presented at the Annual AMS Meeting in January 2024 (Gu et al. 2024) and a major effort is underway to further reduce observation errors for radiances affected by clouds and precipitation.

Improving the Determination of Storm Surge: With its seven-hour revisit time over the tropics, Cyclone Global Navigation Satellite System (CYGNSS) observations of ocean surface winds in the environment and core region facilitate both hurricane weather research and prediction studies. Kang et al. (2024) examined the impact of CYGNSS informed wind fields on storm surge simulations and performed validation studies with high water mark data provided by the US Geological Survey. Storm surge predictions using MERRA-2 wind fields were also performed for comparison using Hurricane Harvey data. Key results were that augmenting existing wind estimates with information provided by CYGNSS has the potential to improve surge predictions relative to existing sources of wind information.

Advancing the Prediction of Precipitation

Incorporating IMERG Early Dataset for Quantitative Precipitation Estimates: Quantitative precipitation estimates (QPEs) are required to support multiple societal applications, including weather forecasting. Since June 2021, Environment and Climate Change Canada (ECCC) has been incorporating the IMERG Early dataset into the Canadian precipitation analysis (CaPA) system as an additional source of QPE, in addition to the usual radar QPEs and surface gauge station reports. Bélair et al. (2024) evaluated the impact that IMERG has on wintertime precipitation analyses generated by CaPA, and developed a configuration for the incorporation of IMERG into CaPA that improves overall performance during the winter season. Case study results showed that IMERG plays a contradictory role in the production of CaPA's precipitation analyses. The analysis displayed physically correct features while also showing unrealistic spatial storm structures, although the latter was improved after incorporating IMERG's quality index. Area averages of the temporal sums of absolute differences between CaPA's analyses with and without IMERG indicated that IMERG Early also can contribute meaningfully over land areas covered by snow, and in areas where air temperature is below -2°C where precipitation is solid phase.

Producing a Gridded Dataset with Climate Generator (CLIGEN): Accurate climate modeling requires long-term, high-resolution, and high-quality time series data. However, such datasets are often not available, especially in the Global South. Fullhart (2023) explored the use of global climate datasets with machine learning to improve global coverage of gridded data. Specifically, a stochastic weather generator, CLImate GENerator (CLIGEN), was developed to produce a gridded dataset, yielding 20-year average point-scale data with a resolution of 0.25° across Africa and South America. Analysis showed that the reformatted gridded dataset provided accurate monthly and daily point-scale values for different variables like mean precipitation. The datasets provide accurate monthly and daily time series precipitation across Africa and South America and offer a critical resource in areas where ground-based observational records are sparse.

Quasi-global Evaluation of IMERG Early Run and GEOS-FP for Real-time Hydrological Monitoring: Precipitation data are key drivers of hydrological simulations, and as a result, reliable QPEs and forecasts are vital for accurate hydrological forecasting. Huang et al. (2023) undertook a quasi-global evaluation of IMERG Early Run (IMERG-E) and forecasted precipitation from NASA's GEOS model with Forward Processing (GEOS-FP) data assimilation to assess their utility in real-time hydrological monitoring and 1–5-day forecasting within a river and hydrologic model. Results showed that the hit bias (i.e., bias for cases that are correctly detected) was the dominant error source of IMERG-E, while the false (i.e., incorrectly detected) precipitation was more important in GEOS-FP. Additional results indicating that GEOS-FP could fill the gap of nowcasting caused by the IMERG-E time latency. For longer lead-time forecasts, the bias diminishes in most regions, likely because the bias in IMERG-E is offset by the misestimations in GEOS-FP.

Characterizing Global Flash Droughts at the Watershed Scale: Addressing impacts of flash droughts (FDs) on the water-food nexus requires an understanding of FD mechanisms and drivers at the watershed level. Neelam and Hain (2024) examined climatic drivers and dry and wet spell lengths from 1980-2019 and analyzed FD characteristics including areal extent, onset time, and duration. Findings revealed substantial variations in FDs among different watersheds. Southern Hemisphere watersheds witnessed expanding, faster-developing, and longer-lasting FDs, which aligns with climate variations in temperature and precipitation. In addition, the onset and duration of FDs are more influenced by the intensity (i.e., magnitude and variability) of climatic drivers than the average length of wet and dry periods. Ultimately, results underscore the need for research to comprehend the interplay between FDs and watershed characteristics for water resource management.

Investigating Warm Season Diurnal Features Along the Yangtze River: Zhu et al. (2023) used 20 years of high-resolution precipitation data from the Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) mission to investigate warm season diurnal features over the complex terrain along the Yangtze River (YR). Key results found that the diurnal amplitudes of precipitation amount and frequency decrease from west to east in general alignment with the decreasing altitude of terrain, while the semi-diurnal amplitudes of precipitation amount and intensity depict a bimodal cycle over the highlands. Small (<200 km^2) precipitation systems contribute the least while large (>6000 km^2) systems contribute the most. The large systems are mainly located in the lowlands at night, with two propagation routes in the morning over the middle and lower reaches of the YR. This sequence of the medium and large systems explains the eastward movement of precipitation intensity along the YR, and merits future dynamic studies.

Assessing the Potential for Moist Convection: Entraining plume models and their underlying assumptions serve as the basis of most global climate model (GCM) convective schemes, oftentimes relying on integrated measures of instability to initiate the convective updraft and subsequent precipitation. Emmenegger et al. (2024) assessed the potential for moist convection through relations derived from profiles of the equivalent potential temperature and the equivalent saturation potential temperature, with weighting of height levels emulating the entrainment process undergone by steady-state plumes. Standard Level 2 radio occultation (RO) data provide the required vertically resolved profiles of pressure, temperature, and partial pressure, and the resulting pseudo-entrainment diagnostic is conditioned on precipitation by space and time matching to nearby GPM and Advanced Technology Microwave Sounder (ATMS) satellite data. The use of RO make these data suitable candidates for the process-oriented diagnostic efforts that isolate physical processes and parameters in GCMs.

Evaluating Madden-Julian Oscillation (MJO) Representation in Climate Models: The MJO is a pattern of atmospheric convection, cloudiness, and rainfall that moves eastward across the Indian and Pacific Oceans over about 30–60 days. The reproduction and understanding of this pattern have long presented a persistent challenge for GCMs. Abraham et al. (2023) examined an 18-year record of relative humidity profiles from AIRS to diagnose and investigate parameterization shortcomings of climate models that prevent them from accurately simulating the MJO. Key results noted large relative humidity anomalies consistent with lower atmospheric moistening occur about 10 days prior to deep convective cores, supporting a ubiquitous role of pre-moistening in MJO propagation.

Electrification and Analysis of Lightning Data

Electrification Within Wintertime Stratiform Regions Samples During the 2020/2022 NASA IMPACTS Field Campaign: Two nor'easter events, sampled during the NASA Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) field campaign, were examined to characterize the microphysics in relation to the underlying electrification processes within wintertime stratiform regions. Harkema et al. (2023) developed a theoretical model to determine whether accretion or diffusional growth regimes were preferential during periods of greatest electrification. The strongest electric fields during the 2020 NASA IMPACTS deployment were associated with large non-rimed ice crystals colliding with each other. Additional results demonstrated that in situ observations provided evidence for the non-riming collisional charging mechanism and that graupel and supercooled liquid water may not be necessary for weak electrification within wintertime stratiform regions.

Assessing Flash Characteristics in Lightning-Initiated Wildfire Events: Schultz et al. (2024) paired 26 years (1995-2020) of lightning data with over 68,000 lightning-initiated wildfire (LIW) reports to understand lightning flash characteristics responsible for ignition. Key results indicated that 92% of LIWs were started by negative cloud-to-ground (CG) lightning flashes and 57% were single stroke flashes. Moreover, 62% of LIW reports did not have a positive CG flash within 10 km of the start location, contrary to the science literature’s suggestion that positive CG flashes are a dominant fire-starting mechanism. Nearly one-third of wildfire events were holdovers, meaning 1 or more days elapsed between lightning occurrence and fire report. The peak current was also not found to be a statistically significant delineator between fire starters and non–fire starters for negative CGs but was for positive CGs. Results highlight the need for reassessing the role of positive CG lightning and subsequently long-continuing current in wildfires started by lightning.

GOES-18 Geostationary Lightning Mapper GLM Full Validation Level Achieved: The Peer/Stakeholders Product Validation Review (PS-PVR) was successfully completed on 8

November 2023 and achieved the Full Validation level for the GOES-18 Geostationary Lightning Mapper (GLM). The team led by William Koshak of Marshall Space Flight Center presented a PS-PVR package that provided extensive details on GLM-18 detection efficiency, false alarm rate, location/time accuracy, and maximum data processing speed. These performance results were determined from validation analyses against ground-based, in situ and space-based reference lightning data.

Improving Atmospheric Models and Prediction

Atmospheric Gravity Waves and Model Validation Using AIRS: Atmospheric gravity waves (GWs) impact the circulation and variability of the atmosphere. Subgrid scale GWs, which are too small to be resolved, are parameterized in weather and climate models. However, some models are now available at resolutions at which these waves become resolved and it is important to test whether these models do this correctly. Lear et al. (2024) used a GW-resolving global simulation from the European Center for Medium-range Weather Forecasts (ECMWF), with a 1.4 km average grid spacing, and compared to observations from the AIRS instrument on NASA's Aqua satellite. The GW amplitudes and momentum fluxes in the model were significantly lower than in the observations. This could be a result of horizontal and vertical wavelengths in the model being underestimated, which helps target refinement for future model development.

Impacts of New Instruments on Prediction: Observing System Simulation Experiments (OSSEs) are trials that investigate the potential performance of proposed new instruments on numerical weather prediction (NWP). As OSSEs involve a framework in which the atmosphere and observations are all completely simulated, it is necessary to validate OSSEs to ensure they are sufficiently realistic to provide useful experimental results.

Privé et al. (2023a) describes calibration and validation of the latest version of the GMAO OSSE framework and demonstrates the superior performance to prior versions of the OSSE. Other recent work described the impacts of a new differential absorption radar for remote measurements of marine surface pressures on numerical weather prediction, in support of the Microwave Barometric Radar and Sounder (MBARS) Instrument Incubator Program project (Privé et al. 2023b). Karpowicz and Privé (2024) investigated the impact of a 2053 nm lidar that can provide three-dimensional winds, finding there was a general reduction in analysis error when wind lidar measurements are added. Finally, McGrath-Spangler et al. (2024) focused on proposed geostationary hyperspectral IR sounders and showed the importance of international coordination with a global ring of Geostationary Extended Observations (GeoXO) sounders for improved NWP skill on a global scale.

Satellite Observations for Sub-Grid Model Parameterization Development: Kahn et al. (2023) produced a two-decade climatology of height-resolved horizontal variance scaling exponents for temperature and specific humidity using AIRS sounding profiles. The AIRS Team Version 6, Version 7, and the Community Long-term Infrared Microwave Combined Atmospheric Product System (CLIMCAPS) retrieval algorithms were compared with reanalysis data. Key results indicated that AIRS provides a global view of scale-dependent variance and skewness that is useful for sub-grid parameterization development and validation of weather and climate prediction models.

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