Over Thirty Years Reporting on NASA's Earth Science Program

The Earth Observer

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The Editor's Corner

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On May 7, 2023, at 9:00 PM Eastern Daylight Time (EDT), Rocket Lab successfully launched an Electron rocket from Launch Complex 1 in New Zealand, which carried the first two 3U CubeSats[1] of the Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission into orbit. Following launch, the rocket's kick stage, which is normally used on Electron launches to circularize the orbit, performed the inclination change needed to place the payload in the required 550-km orbit at an inclination of 32°. The two 3U CubeSats were released 35 minutes after liftoff, and then—after a tense 20 minutes—the successful deployment was confirmed when a ground station acquired the signal from both of the satellites.

A second Electron launch took place May 26, 2023, at 11:46 PM EDT—from the same location and following a similar sequence of events—and successfully deployed two more 3U CubeSats to complete the TROPICS constellation.

[1] CubeSats are built to standard dimensions, or *units* (U) of 10 cm x 10 cm x 10 cm. They can be 1U, 2U, 3U, or 6U in size, and typically weigh less than 1.33 kg (3 lbs) per U.

continued on page 2

Photo 1. On May 7, 2023, at 9:00 PM Eastern Daylight Time (EDT), Rocket Lab successfully launched an Electron rocket from Launch Complex 1 in New Zealand, which carried the first two 3U CubeSats of the Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission into orbit. A second Electron launch took place May 26, 2023, at 11:46 PM EDT, carrying two more of the TROPICS CubeSats into orbit. Each CubeSat flies a microwave radiometer that can retrieve temperature and water vapor profiles. With four satellites flying in formation, TROPICS will be able to get hourly updates that can aid in monitoring the development of hurricanes and other tropical weather systems. Scientists look forward to having the TROPICS constellation operational for the bulk of the Atlantic Hurricane Season—which began on June 1. **Photo credit:** Rocket Lab

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Each CubeSat flies a microwave radiometer that can retrieve temperature and water vapor profiles. With four satellites, TROPICS will be able to get hourly updates that can aid in monitoring the formation of hurricanes and other tropical weather systems.[2]

The original plan called for launches from Rocket Lab's U.S. site at the Mid-Atlantic Regional Spaceport at NASA's Wallops Flight Facility. However, in April 2023, Rocket Lab decided to move the two launches to its facility in New Zealand—at no additional cost to NASA—so that the constellation would be in place in time to monitor the 2023 Atlantic Hurricane Season that began on June 1. Congratulations to the TROPICS team—including principal investigator **William Blackwell** [MIT].

NASA Headquarters' (HQ) Earth Science Division (ESD) held a virtual Terra, Aqua, and Aura Data Continuity Workshop on May 23–25, 2023. The community workshop, a follow-on to a Request For Information (RFI) that was released on March 1 and closed on April 4, provided a forum to discuss EOS flagship mission data product continuity needs, current capabilities, gaps, and potential ESD activities to minimize continuity losses after mission terminations. The RFI responses were used in planning the workshop agenda around the following science disciplines: Atmosphere and Earth Radiation Budget, Land, Ocean, Ozone and Trace Gases, and Infrared/Microwave Sounding. The workshop organizers, led by **David Considine** [NASA HQ, ESD—*Rotating Deputy Associate Director for Climate and Weather Research*] and **Jim Gleason** [GSFC—*Suomi NPP Project Scientist* and *JPSS Senior Project Scientist*], are working on a workshop report to be delivered to ESD. The three flagship EOS missions were invited to the 2023 ESD Senior Review for continuing missions following last November's Terra, Aqua, and Aura Drifting Orbits Workshop.[3] Results from the Senior Review process are expected to be announced in mid-to-late summer.

NASA's Land-Cover and Land-Use Change (LCLUC) program celebrated its twenty-fifth anniversary with a LCLUC science team meeting (STM) in October 2022. The meeting included an evening "Silver Jubilee" celebration at which **Jack Kaye** [NASA HQ, ESD—*Associate Director for Research*] gave remarks, along with a well-attended poster session that provided an impetus for lively discussion among the 32 presenters and participants.

Initiated in 1996, the LCLUC program remains unique within NASA, as it seeks to combine remote sensing and social science to understand how humans use the land and the management decisions they make. Over the last quarter-century, LCLUC ST members have documented major changes in land use over large areas of the world and the unprecedented rapid rates of change, e.g., agricultural expansion in South America, deforestation throughout the tropics, and urban expansion in China. With the increasing global population and associated pressures for land and natural resources, such changes will continue—and accelerate—making effective land management crucial to our response to climate change. Whether managing the effects of extreme weather on agriculture, the impact of heatwaves on urban communities, mitigating emissions from Agriculture Forestry or Other Land Uses (AFOLU), or implementing sustainable water management and climate resilient agricultural practices, land use is a central interdisciplinary theme.

[2] TROPICS planned to deploy a six-satellite 3U CubeSat formation. Regrettably, the first two CubeSats were lost when the Astra 3.3 rocket carrying them failed to reach orbit in June 2022. The Astra 3.3 rocket was subsequently retired. NASA awarded the contract for the remaining two TROPICS launches to Rocket Lab in November 2022—under its Venture-class Acquisition of Dedicated and Rideshare (VADR) contract.

[3] To learn more about this workshop, see **"NASA Holds Discussions About the Future of the EOS Flagship Missions,"** in the January–February 2023 issue of *The Earth Observer* [**Volume 35**, **Issue 1**, pp. 13–17].

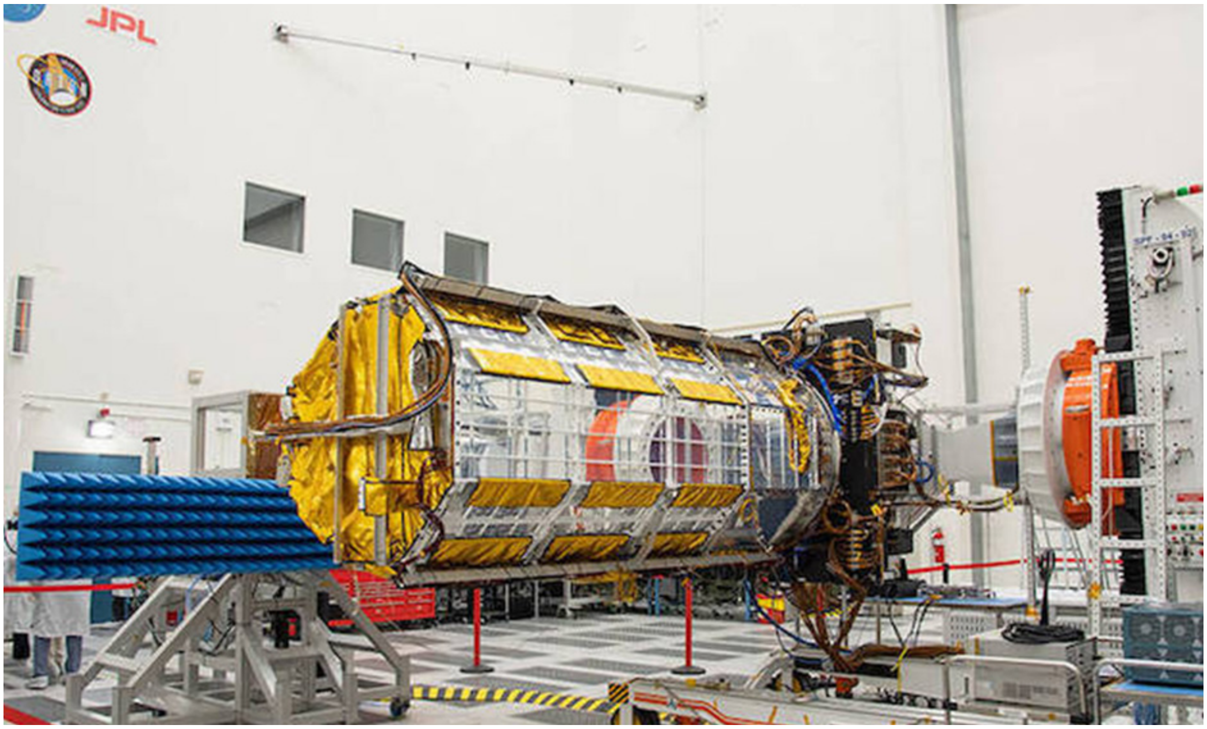

Photo 2. The scientific instrument payload for the NISAR mission sits in a JPL clean room. On March 6, 2023, the instrument safely arrived in Bengaluru, India, where engineers from JPL are working with their ISRO counterparts to prepare the payload for integration with the spacecraft bus for testing. Launch is scheduled to occur in 2024. **Photo credit:** NASA/JPL-Caltech

The LCLUC program is now part of NASA's Earth Science Carbon Cycle and Ecosystems research focus area. The program has several components, which can be grouped into three themes: detection and monitoring; impacts and consequences; and drivers, modeling, and synthesis.

Turn to page 12 of this issue to read more about the twenty-fifth anniversary LCLUC STM.

Turning now to ongoing missions, **"The Editor's Corner"** of the January–February 2023 issue of *The Earth Observer* reported on the successful launch of NASA's Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission on April 7, 2023. The Intelsat 40e Spacecraft is now in its orbital slot positioned at 91°W longitude. On June 7, 2023, the TEMPO instrument was powered on. First-light images are expected in late July, followed by an intensive period of on-orbit instrument characterization activities until October, after which the first Level-2 science data products will be released. All telemetry data continues to be nominal.

A joint science meeting for the TEMPO, Geostationary Extended Operations (GeoXO) Atmospheric Composition Instrument (ACX) and Tropospheric Ozone Lidar Network (TOLNet) programs took place May 1–5, 2023 at the University of Alabama, Huntsville. Approximately 400 people attended this hybrid event (120 participated in person). The theme for the meeting was "Building the Pathway from TEMPO to GeoXO." This joint meeting brought together the TEMPO Science Team and Early Adopters Program along with the GeoXO and TOLNet Science Teams to facilitate the coordination and long-term planning of air quality observations over North America from Geostationary Earth Orbit.

Turn to page 5 of this issue to read more about the TEMPO mission.

After nearly four years on orbit, the Global Ecosystem Dynamics Investigation (GEDI) has ceased operations—at least for the next 18 months. Originally planned as a two-year mission, GEDI was extended

List of Acronyms Used in Editorial and/or Table of Contents

EOS	Earth Observing System
GSFC	NASA's Goddard Space Flight Center
GSLV	Geosynchronous Satellite Launch Vehicle
ISRO	Indian Space Research Organisation
JPL	NASA/Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
MIT	Massachusetts Institute of Technology
NOAA	National Oceanic and Atmospheric Administration

until March 2023 to accomplish its baseline science mission goals, which were delayed by changes to the orbit of the International Space Station (ISS). GEDI collected more than 20 billion high quality observations of the vertical structure and height of the Earth's forests, as well as bare ground and water body elevations. Data from GEDI are being used for a wide range of applications, including biomass estimation, habitat characterization, and wildfire prediction. GEDI's maps of biomass are unique in both their accuracy and their explicit characterization of uncertainty, and are a key component in the estimation of aboveground carbon stocks. These estimations help quantify the impacts of deforestation and subsequent regrowth on atmospheric carbon dioxide concentration.

Calls from a variety of stakeholders to keep GEDI in space led NASA HQ to review the mission in December 2022 for a potential extension. Based in part on GEDI's unique, timely data and the instrument showing few signs of degradation, NASA decided that the mission should continue, at least through 2026 (provided that space could be found on the ISS). Once the decision to extend the mission was final, NASA released a statement explaining that "demand is high for external attachment points on the station, and GEDI is scheduled to be temporarily replaced by a Department of Defense payload after more than four years of operations. However, the agency is planning to keep the instrument in space and reinstall it to continue through the life of the space station." The hope is that GEDI can be reinstalled in its original location on the JEM-EF in the fall of 2024.

Looking now to future mssions, the scientific payload of the NASA–ISRO Synthetic Aperture Radar [NISAR] mission—shown in **Photo 2**—touched down in Bengaluru, India, on March 6, where engineers from JPL are working with their ISRO counterparts to prepare the payload for integration with the spacecraft bus for testing and launch in 2024 aboard an ISRO GSLV Mark II rocket. The payload, which consists of L-band and S-band radar systems, arrived at ISRO's U R Rao Satellite Center aboard a U.S. Air Force cargo plane in a specially designed, climate-controlled shipping container.

Observing Earth in all weather conditions, day and night, NISAR will provide a dynamic, three-dimensional view of Earth's land and ice surfaces in unprecedented detail. Over the course of its three-year prime mission, the satellite will scan those surfaces twice every 12 days, using its dual radar systems to study movements down to fractions of an inch. The roughly 100 petabytes of data it returns will advance scientific understanding in a broad range of Earth science fields, including ecosystems and their response to climate change; the cryosphere; solid Earth; disaster response; and soil moisture.

NISAR is a joint mission between NASA and ISRO that grew from a cooperation agreement the two agencies signed in 2014. JPL built the L-band synthetic aperture radar (SAR). NASA is also providing NISAR's radar reflector antenna, the deployable boom, a high-rate communication subsystem for science data, global positioning system satellite (GPS) receivers, a solid-state recorder, and payload data subsystem. ISRO is providing the spacecraft bus, the S-band SAR, the launch vehicle, and associated launch services and satellite mission operations.

Last but not least, NASA has selected the **Polarized Submillimeter Ice-cloud Radiometer** (PolSIR) as the winning proposal for the **Earth Venture** Instrument–6 (EVI-6) Announcement of Opportunity.[4] This mission consitsts of two identical CubeSats—each just a bit over a foot in length—that will study clouds that form at high altitudes throughout tropical and sub-tropical regions to better understand their diurnal variability and, in particular, how their ice content changes. This information will serve as crucial and unique input to global climate models, and help lead to more accurate simulations of these high-altitude clouds. Congratulation to the PolSIR team, including principal investigator **Ralf Bennartz** [Vanderbilt University] and Deputy PI **Dong Wu** [GSFC]. ■

[4] EVI missions are for the development of lower-cost instruments with a targeted research goal, which typically catch a ride along with another mission or commercial satellite in order to minimize launch costs.

TEMPO: Revolutionizing Atmospheric Chemistry Measurements from Space

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While the majority of the text in this article was originally printed as a **prelaunch brochure for TEMPO**, the text has been rearranged and modified in places to make it more suitable for publication in *The Earth Observer*.

Introduction

The air we breathe is composed of a mixture of atmospheric gases and aerosols, the exact composition of which varies at any given moment depending upon a host of environmental factors. The emissions from both naturally occurring (e.g., lightning, sea surface spray, fires) and/or human-produced sources (e.g., automobiles, trucks, power plants, wildfires, and cargo ships) combine to produce surface-level ozone and other pollutants. For decades, satellite-based instruments have provided insights into the physical and chemical processes that influence Earth's atmosphere and contribute to air pollution, impacting not just human health, but ecosystems worldwide.

NASA's Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission will revolutionize how atmospheric chemistry is measured and tracked from space. TEMPO will be the first space-based instrument to monitor major air pollutants across North America every daylight hour at high spatial resolution.[1] TEMPO will measure four of the six criteria air pollutants tracked by the U.S. Environmental Protection Agency (EPA) as part of enforcing the Clean Air Act; these include nitrogen dioxide (NO_2), ground level ozone (O_3), sulfur dioxide (SO_2) and particulate matter with diameters less than 2.5 µm ($PM_{2.5}$).

Pollutants frequently undergo rapid chemical reactions during downwind transport, resulting in a lack of comprehensive observations of their transport and transformation. While increasingly powerful satellite-based instruments have provided us with

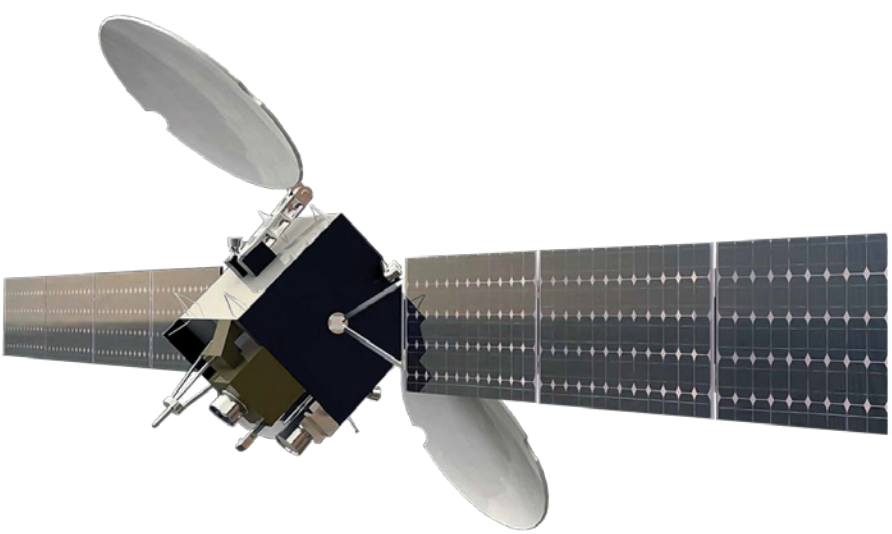

Figure 1. Artist's rendering of the TEMPO satellite. **Image credit:** NASA

[1] To learn more about the TEMPO mission, see **"NASA Ups the TEMPO on Air Quality Monitoring,"** in the March–April 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 2**, pp. 10–15]. To learn about plans to use TEMPO to make satellites observations of air quality over the Gulf of Mexico see **"NASA Tracks the SCOAPE of Offshore Oil and Gas Pollution Using Satellite and Ship Cruise Measurements,"** in the July–August 2022 issue of *The Earth Observer* [**Volume 34**, **Issue 4**, pp.5–17].

critical insights into the physical processes that govern our atmosphere, even the latest technologies face a significant difficulty when studying air pollution: their data have limited temporal resolution. Early air quality instruments circled the Earth once per day in line with the Sun, meaning they could only measure air quality over a particular region every 24 hours. For several decades, this has prevented researchers from answering some of the most pressing questions relating to air quality, including precisely how much pollution is being emitted, where it comes from, and how it varies over time.

To allow for more frequent sampling. TEMPO has been placed in geostationary orbit—the position where satellites remain at the same point relative to Earth's surface by orbiting above its equator, with an orbital time matching Earth's rotation. This will allow the satellite to continuously monitor the same area on the Earth's surface, and measure air quality once per hour at any given location during the day. TEMPO measures, directly or by proxy,[2] the major elements of tropospheric ozone chemistry, scanning for pollution across the contiguous U.S. Measurements include lower tropospheric O_3, NO_2, and formaldehyde (HCHO), glyoxal (OHCCHO) linear, or $C_2H_2O_2$, water vapor, halogen oxides, aerosols (i.e., $PM_{2.5}$), clouds, ultraviolet (UV)-B radiation, and foliage properties. A global team of scientists, led by **Kelly Chance** [Smithsonian Astrophysical Observatory (SAO)—*Principal Investigator*], will analyze these measurements of North American pollution—the most in-depth to date—as they affect both natural environments and our own health.

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By leveraging high spatial and temporal resolutions, TEMPO will be able to pinpoint where pollution is coming from, and how particular sources vary over time. "TEMPO will track pollution loading, transport, and transformation," explains Chance. "It also will provide near-real-time air quality products, measure the key elements of air pollution chemistry, and measure the UV exposure index."

A Constellation of Geostationary Satellites

TEMPO will be collecting data during a timeframe when two other geostationary pollution-monitoring satellites from Asia—Geostationary Environment Monitoring Spectrometer (GEMS) on the Geostationary–Korea Multi-Purpose Satellite-2 (GEO-KOMPSAT 2B)—and Europe—Sentinel-4 on the Meteosat Third Generation Sounder (MTG-S)—will also be in operation. Together, the three instruments will form a geostationary air quality (Geo-AQ) constellation—as shown in **Figure 2**.

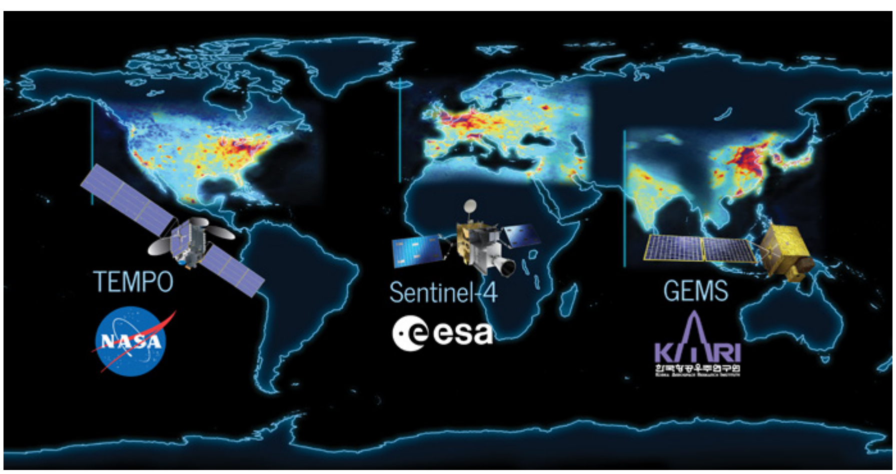

Figure 2. Pollution-monitoring instruments from NASA, the European Space Agency (ESA), and the Korea Aerospace Research Institute (KARI) will together form a geostationary air quality (Geo-AQ) constellation. **Image credit:** Tim Marvel/NASA

[2] Formaldehyde is one of the most abundant non-methane volatile organic compounds (NMVOC) in the troposphere. It is also highly reactive, meaning it has a lifetime of only a few hours in the troposphere. These properties make it a useful proxy for measuring NMVOC emissions in satellite observations.

The Korea Aerospace Research Institute (KARI) launched GEMS on February 18, 2020. Like the TEMPO instrument itself, the GEMS instrument was built by Ball Aerospace in Boulder, CO. As a result, the two instruments share many design elements; the GEMS spectrometer also observes the UV and visible (VIS) parts of the spectrum. The Sentinel-4 spectrometer is scheduled for launch in 2024 and will observe the UV, VIS, and—unlike TEMPO—near-infrared (NIR) portions of the spectrum.

The combination of Geo-AQ and other instruments currently in low Earth orbit (LEO) making global (but less frequent) observations, creates an atmospheric composition *virtual constellation* (AC-VC),[3] able to measure atmospheric pollution down to a spatial resolution of 4 mi^2 (10 km^2).

The AC-VC will measure these pollutants, which primarily include O_3, NO_2, HCHO, and tiny atmospheric particles (aerosols), in unprecedented detail and frequency.

Mission Overview and Launch Details

TEMPO was selected in 2012 as NASA's first Earth Venture Instrument (EVI) mission. The TEMPO Science Team includes members from NASA's Langley Research Center (LaRC), NASA's Goddard Space Flight Center (GSFC), the National Oceanic and Atmospheric Administration (NOAA), and the Environmental Protection Agency (EPA).

The satellite platform, manufactured by Maxar in Palo Alto, CA, is based on the Maxar 1300-class spacecraft platform—see **Photo** [*right*]. After integration with Intelsat's 40e (IS-40e) commercial communications satellite, the entire spacecraft underwent a rigorous environmental test campaign, conducted by Maxar, to verify that the satellite—including the TEMPO instrument—will survive launch challenges, and will demonstrate sustained operations in geostationary orbit.

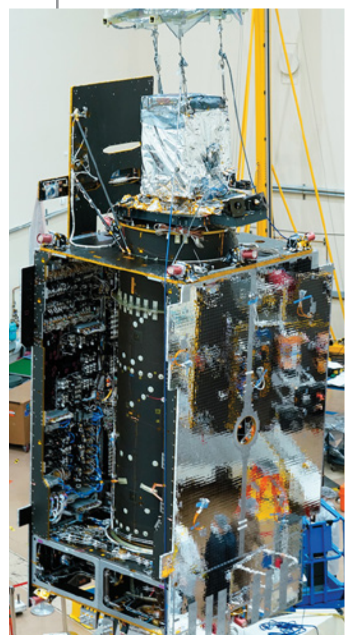

Photo. The TEMPO instrument rests atop Maxar's Intelsat 40e satellite in Palo Alto, CA. **Image credit:** Maxar

The spacecraft was shipped from Maxar to the Cape Canaveral Space Force Station in Florida; launch took place on April 7, 2023, at 12:30 AM EDT on a SpaceX Falcon 9 rocket. From there TEMPO maneuvered into *geostationary orbit*. This position enables TEMPO to "sweep" North America once every hour, providing a unique vantage point to continuously observe the continent. The IS-40e is designed for an operational lifespan of 15 years. The TEMPO instrument design life is on the order of two years. However, NASA has negotiated optional hosting of TEMPO beyond the prime mission duration in two year blocks for approximately ten years

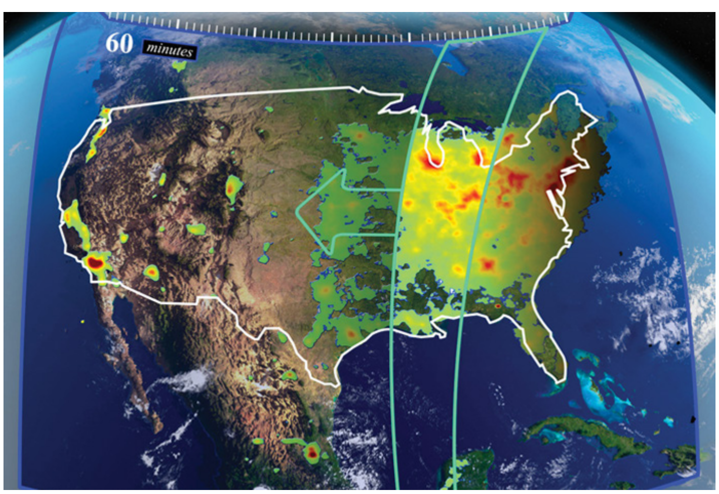

Figure 3. Graphic depicting TEMPO's perspective from geosynchronous orbit. This vantage point will enable TEMPO to monitor daily variations in air pollution from the Atlantic to the Pacific, and from Mexico City and the Yucatan Peninsula to the Canadian oil sands. **Image credit:** NASA

[3] To learn more about the AC-VC, see **"Geostationary Orbit as a New Venue for Earth Science Collaboration: Eleventh CEOS Atmospheric Composition Constellation Workshop"** in the July–August 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 4**, pp. 17–22, 24].

total, with the Geostationary Extended Operations (GeoXO) satellites assuming air quality duties over North America thereafter.

The hourly data from NASA's TEMPO mission bring new possibilities to conduct in-depth analyses of North American pollution—see **Figure 3** below. TEMPO will be able to collect pollution data covering Mexico, the U.S., and Canada on an hourly basis during daytime, and will examine a large region that is home to a diverse array of communities, species, and environments. These hourly measurements made from geostationary orbit capture the high variability present in the diurnal cycle of emissions and chemistry that are unobservable from current LEO satellites that measure once per day.

The TEMPO Instrument: Harnessing the Power of Spectroscopy to Study Earth's Atmosphere

The TEMPO instrument consists of a grating spectrometer, sensitive to UV and VIS wavelengths of light, attached to the Earth-facing side of IS-40e. Instrument characteristics are found in **Table 1** below.

Table 1. TEMPO Instrument Characteristics.

TEMPO Characteristics	
Spectral Range	293–493 nm ultraviolet, 537–741 nm visible
Spectral Resolution	0.6 nm
Spatial Resolution	2.0 km (1.4 mi) per pixel north–south, 4.7 km (2.9 mi) per pixel east–west at center of field of regard
Scan Frequency	1 hour during daylight
Max Data Rate	66 Mbps
Mass	137 kg (302 lb)
Volume	1.4 m x 1.1 m x 1.2 m (4.6 ft x 3.6 ft x 3.9 ft)
Average Power	132 W

The nadir view allows TEMPO to maintain a constant view of North America for the instrument's light-collecting mirror to make a complete east-to-west scan of the *field of regard*[4] during each hour of the daytime, as shown in **Figure 3** on page 7.

The instrument's optical system resolves pollution levels to regions of several square miles per pixel as opposed to existing limits of about 100 square miles, so that

[4] *Field of regard* refers to the total area that can be captured by a movable sensor. This is not to be confused with the field of view, which is the angular cone perceivable by the sensor at a specific time.

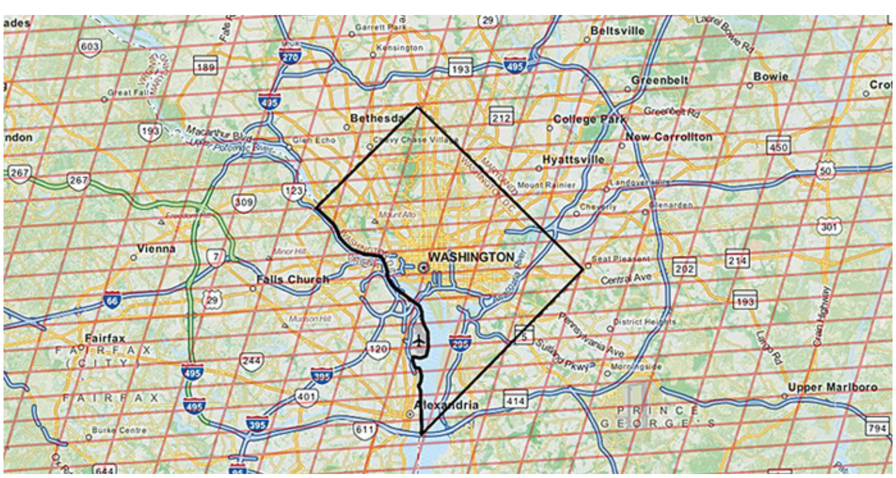

Figure 4. TEMPO will be able to resolve pollution at sub-urban scales. Each orange rectangle represents the footprint of a single pixel. **Image credit:** ©OpenStreetMap contributors/Harvard & Smithsonian Center for Astrophysics (CfA)

pollution can be tracked at sub-urban scales—see **Figure 4**. Concentrations of some pollutants vary significantly throughout the course of the day—and from day to night. The high spatiotemporal resolution of the TEMPO dataset will enable tracking of these variations in the concentrations of pollutants in much more detail than current observations allow. This will provide researchers, air quality managers, and policy makers with improved ability to track the changing "chemical weather" locally, regionally, and across the continent.

By measuring sunlight reflected and scattered from Earth's surface and atmosphere back to the instrument's detectors, TEMPO's UV and VIS sensors will provide the spectra of various trace gases that are important for understanding air quality, as noted earlier—see **Figure 5** below.

The TEMPO instrument relies on two major components: the control electronics, which are installed within the host spacecraft and provide the communications link to the sensor, and the nadir deck subsystem, which is mounted on the Earth-facing side of the spacecraft. The nadir deck subsystem includes the sensor, the telescope assembly, the focal plane assembly, the sensor heat sink, and the focal plane electronics. The light reflected and scattered from Earth is focused onto a *diffraction grating* where the light is dispersed into spectra before being detected by a charge-coupled device (CCD) chip on the focal plane—see **Figure 5**.

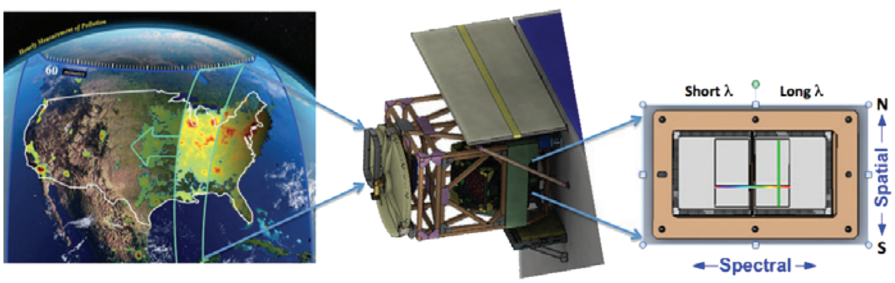

Figure 5. The light from one vertical stripe on Earth's surface enters the TEMPO spectrometer instrument and is projected onto a detector that measures reflected and scattered sunlight, enabling TEMPO's ultraviolet and visible light sensors to provide spectra of ozone, formaldehyde, nitrogen dioxide, and other elements of daily atmospheric chemistry cycles. **Image credit:** NASA/BATC/CfA

Transforming Data Products into Actionable Information

The planned TEMPO data products are listed in **Table 2** on page 10. TEMPO data will not only improve the ability to describe atmospheric composition across North America but also are expected to empower the public to utilize these data. In order to supply the public with NRT pollution reports and forecasts, planning is underway to create website and mobile applications that feature combined TEMPO data and regional air-quality models, which will improve EPA air-quality indices.

For TEMPO data to achieve their full potential they must be available with sufficiently *low latency* (i.e., available soon after they are acquired) so that they can be used to create public policy, improve weather and other forecasts, or inform NRT reports addressing air pollution. Such applications also require that the data be conveniently accessible by the user community. To achieve these requirements, TEMPO data products will be transferred continuously to NASA's Atmospheric Science Data Center (ASDC) in Hampton, VA, to be archived and later distributed to the public. Standard tools and services at ASDC can be used to search, visualize, and subset TEMPO data. In addition, TEMPO data can also be directly accessed for easy and quick visualization and subsetting from the **Environmental Protection Agency's Remote Sensing Information Gateway** (RSIG) application. The **TEMPO Early Adopters Program**, which actively engages diverse groups of individuals and organizations to expand their knowledge and abilities in using TEMPO data for applied research, will collaborate with ASDC through TEMPO **Early Adopter workshops** and tutorials, gathering direct feedback from the user community.

Once in space, commands will be issued to TEMPO through the Instrument Operations Center (IOC), which is based at the SAO in Cambridge, MA—see **Figure 6** below.

The IOC will have the capability to send real-time commands to the instrument, allowing TEMPO to monitor sudden and relatively short-lived environmental events—e.g., wildfires or volcanic eruptions. Raw data collected by TEMPO will be relayed to the Science Data Processing Facility, also located at the SAO, and processed into the data products listed in Table 2. The SAO intends to produce NO_2 and several other species at native resolution.

Table 2. Descriptions of TEMPO Data Products

<table>
<tr><th>Level</th><th>Product</th><th>Major Outputs</th><th>Resolution (km²)</th><th>Frequency/Size</th></tr>
<tr><td>0</td><td>Digital counts</td><td>Reconstructed Digital Counts</td><td>2.0 × 4.7</td><td>Daily, Hourly</td></tr>
<tr><td>1</td><td>Irradiance</td><td>Calibrated and Quality Flags</td><td>N/A</td><td>Daily</td></tr>
<tr><td>1B</td><td>Radiance</td><td>Geolocated, Calibrated Solar Backscattered Radiances</td><td>2.0 × 4.7</td><td>Hourly/Granule</td></tr>
<tr><td rowspan="8">2</td><td>Cloud</td><td>Cloud Fraction and Cloud Pressure</td><td>2.0 × 4.7</td><td rowspan="8">Hourly/Granule</td></tr>
<tr><td>Ozone (O_3) Profile</td><td>Total, Stratospheric, Tropospheric, and 0–2 km Column</td><td>8.0 × 4.7</td></tr>
<tr><td>Total column O_3</td><td>Total Column, Aerosol Index (AI)</td><td>2.0 × 4.7</td></tr>
<tr><td>Nitrogen dioxide (NO_2)</td><td>Stratospheric and Tropospheric Vertical Column Densities (VCD)</td><td>2.0 × 4.7</td></tr>
<tr><td>Formaldehyde (HCHO)
Glyoxal ($C_2H_2O_2$)
Water vapor (H_2O)
Bromine monoxide (BrO)
Sulfur dioxide (SO_2)</td><td>Total VCD</td><td>2.0 × 4.7</td></tr>
<tr><td>Aerosol</td><td>Absorbing AI, Ultraviolet (UV) and Visible Aerosol Optical Depth, UV Single Scattering Albedo, and Aerosol Optical Centroid Height</td><td>8.0 × 4.7</td></tr>
<tr><td>TEMPO/GOES-R Synergistic</td><td>Radiance, Aerosol, Cloud Mask, Fire/Hotspot, Lightning, and Snow/ice</td><td>2.0 × 4.7</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>3</td><td>Gridded Level-2 (L2) Products</td><td>Same as L2 Products</td><td>2.0 × 2.0</td><td>Hourly/Scan</td></tr>
<tr><td>4</td><td>Ultraviolet (UV)–B</td><td>UV Irradiance, Erythemal Irradiance, and UV Index</td><td>2.0 × 4.7</td><td>Hourly/Scan</td></tr>
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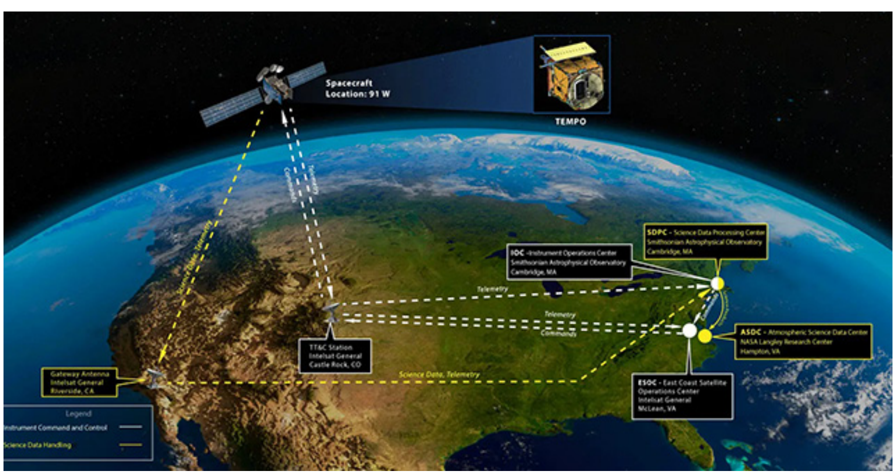

Figure 6. TEMPO operations architecture. **Image credit:** NASA

The fine resolutions of TEMPO data will be better at constraining emissions that lead to air quality exceedances and is ideally suited for assimilation into chemical models for air quality forecasting. The high spatial and temporal resolution of TEMPO observations will provide new insight into the identity and timing of the emission sources and atmospheric drivers of air pollution distribution at sub-urban scales.

As noted earlier, TEMPO measurements will be a powerful tool for observing and assessing pollution's impact on human health. Hourly estimates of gaseous air pollutants from TEMPO will be included as inputs for air-pollution exposure calculations needed to understand the health effects of air pollution. For example, harmful air pollution levels may lead to notifications or prompts for specific patients to avoid physical exertion or to stay indoors when possible. This usage can also underscore the importance of effective disease management, whereby individuals who live in areas with chronically higher levels of air pollution can be encouraged to see their doctor for a medical checkup. The ability to observe and attribute air pollution events over the entire TEMPO field of view offers a wide breadth of promising policy and societal benefits.

While the TEMPO mission will improve understanding of important air quality emissions over greater North America, the mission plans to use as much as 25% of the observing time for special operations. A focus of the special operations will be disaster events—e.g., wildfires, dust storms, volcanic eruptions, and industrial accidents, along with unique chemistry experiments aimed at further enhancing our understanding of rapidly varying emissions and air pollutants in complex environments.

While the TEMPO mission will improve understanding of important air quality emissions over greater North America, the mission plans to use as much as 25% of the observing time for special operations.

These operations can be performed in the first four months after launch during the commissioning phase of the mission. The special scan mode can be easily initiated a few days after notice of an impending or occurring event, with the potential to initiate observations about an hour after notification of the event. There is also considerable flexibility in the specifications of temporal frequency (e.g., ≤ 10 min) and swath width with the special scans.

To maximize the value of both *standard* (hourly) and special observations from TEMPO, planning and coordination activities began during the prelaunch period of the mission. Early Adopters can have an impactful role in the planning activities by submitting experiment requests for the standard and special observations from TEMPO. Descriptions of experiment requests can be found in the **TEMPO Green Paper**, which is a "living document" that is being routinely updated with new experiments from the community and input from early adopters addressing a wide spectrum of science applications. This document gives a comprehensive view of the many applications that will benefit from this new source of higher-resolution air quality data and enhances mission planning activities.

Conclusion

As the first space-based instrument to monitor major air pollutants across North America every daylight hour at high spatial resolution, the TEMPO mission will revolutionize the way scientists study air pollutant emissions— from determining the quantity of emissions, pinpointing their naturally occurring or anthropogenic origins, to analyzing changes over time.

A single component within a larger constellation of geostationary satellites, TEMPO will provide NRT data products that will significantly improve air quality forecasting around the most densely populated areas of the Northern Hemisphere. These data can become predictive indicators for damage to biological systems and the general environment. By empowering the public with tools to easily utilize these data, and through engagement activities like the Early Adopters program, RSIG application, and the TEMPO Green Paper, the future of TEMPO data looks promising for a growing number of health, environmental, and air quality applications that will benefit society for years to come. ■

NASA's Land-Cover and Land-Use Change Science Team Celebrates 25 Years

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Introduction

The 2022 NASA **Land-Cover and Land-Use Change** (LCLUC) Science Team (ST) Meeting took place October 18–20 at the Hyatt Regency Bethesda, MD. More than 130 people participated in the event—see bottom photo in the sidebar on page 14—including current and former principal investigators, team members, and invited guests from NASA Headquarters (HQ) and national and international partner programs. The meeting also provided a timely opportunity to reflect on the program's achievements over the past quarter century and to identify current research challenges and future directions. The sessions covered presentations on various land-use and land-cover change themes, including past, current, and future Earth observation missions, data and products, national and international program partnerships, LCLUC regional research programs, and emerging LCLUC topics. Invited speakers from Europe shared their experiences, and newly funded projects were presented through posters. Panel sessions were organized to discuss critical issues and improve ongoing research projects. The meeting was successful in promoting collaborations and partnerships among LCLUC researchers and collecting community feedback to keep the LCLUC program aligned with community needs.

This report begins with a brief synopsis of the origins of the LCLUC, an early success story, and the current state of the program. The remainder of the article summarizes the presentations and discussions that took place during the meeting—see page 13 to learn more about the *Silver Jubilee and Poster Session*. Refer to the **full agenda** to learn more and to view presentations.

Origins of the LCLUC

Bob Harriss [NASA HQ—*NASA Earth Science Director* at that time, now deceased] initiated the LCLUC Program in 1996.[1] **Anthony "Tony" Janetos** [then NASA Terrestrial Ecology Deputy Program Manager, now deceased—shown in **Photo 1**, *right*], who would become the first LCLUC program manager, wrote a white paper in 1995 that outlined the underlying philosophy of the program. The objective of the program would be to further understand the consequences of land-use change in continuing to provide ecological goods and services, particularly in the face of requirements for sustainable management, direct human influences, and a generally expanding human population. The ultimate vision of the program was—and is—to develop the capability to perform repeated inventories of LCLUC from space and develop the scientific understanding and models necessary to evaluate the consequences of observed changes.

Photo 1. Tony Janetos was the first LCLUC ST program manager.

The LCLUC program's round of funded proposals started in 1996, with Chris Justice [University of Maryland, College Park (UMD)] being appointed as Program Scientist (later renamed Project Scientist). He organized the first LCLUC ST Meeting at Airlie House in Warrenton, VA, in 1997. Justice still holds the Project Scientist role today and has been present for all the ST meetings that have taken place—see *LCLUC STM Group Photos Through the Years* on page 14.

[1] Bob Harriss passed away in 2021. To read an "**In Memoriam**," see the January–February 2022 issue of *The Earth Observer* [**Volume 34**, **Issue 1**, p. 4].

LCLUC Silver Jubilee Celebration and Poster Session

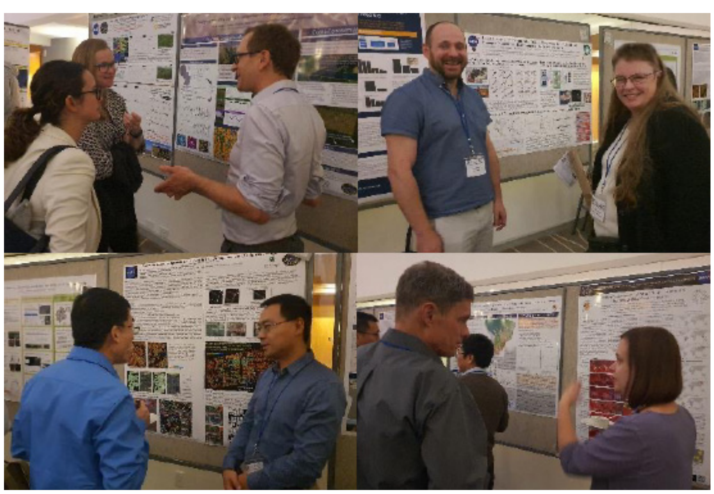
The first evening of the meeting, there was a Silver Jubilee celebration. Participants enjoyed the opportunity to meet in person and reminisce about the past 25 years of LCLUC Science Team activities and look towards a bright future for land use/land change studies. The gathering was particularly meaningful after the long involuntary hiatus in meeting together imposed by COVID-19.

The featured speaker for the evening was **Jack Kaye** [NASA Headquarters, Earth Science Division—*Associate Director for Research* (*shown left)*] who delivered prerecorded remarks. He congratulated the LCLUC Program on its Silver Anniversary and expressed his regrets for not being able to attend in person. He mentioned some of the program's unique aspects and emphasized its importance in NASA's Earth Science Division. Kaye said that LCLUC is unique because it integrates natural and social sciences—as reflected in its solicitations. This integration is important as it helps with understanding the role of humans and socioeconomic systems in modifying Earth's surface.

Not only does LCLUC have a unique programmatic mission but, over the past 25 years, it has incorporated aspects that make it distinctive from a programmatic perspective. As examples, Kaye cited the consistent use of a *two-step solicitation process*—which streamlines the number of submissions into a competitive bunch, thereby reducing the burden on proposers having to write full proposals at the first evaluation step and also having to write a full proposal while also reducing the number of proposals that the review panel needs to evaluate—keeping the success rate to a reasonable 30%. He also noted the LCLUC STM's habit of running early-career investigator solicitations that continuously infuse younger talent into the Program and sustain vitality and scientific continuity. He also pointed out that the LCLUC program is well coordinated both within the U.S. and internationally—with many domestic and international partnerships—and has also developed good links to the commercial sector.

Kaye noted that the **2017 Earth Science Decadal Survey** calls for amplifying the cross benefits of Research and Applications, and the LCLUC Program has been involved in such activities, providing foundational science. The LCLUC Program is also at the forefront of capacity building and training in various regions of the world, working with national space agencies and international programs. Meetings, webinars, and training sessions of the LCLUC Program have helped the younger generation in developing their scientific careers. The program has achieved many important accomplishments over the past 25 years, and its leadership is appreciated. The goal is to continue making a difference in the lives of people around the world and promote the use of NASA data, methods, and products for societal benefits.

In addition to Kaye's remarks, there was a poster session with 32 participants. The poster session was well attended and there were vibrant discussions among participants—see photos below. A list of posters—with links to PDFs of some—can be accessed at the **meeting website**.



LCLUC "Silver Jubilee" participants interact during the poster presentations, which showcased the latest LCLUC science results. **Photo credit:** Rohan Purekar and Keelin Haynes/UMD LCLUC Team

The LCLUC program's foundation can be traced back to a number of data initiatives in the early 1990s, such as the NASA Landsat Pathfinder project led by **David Skole** [then at University of New Hampshire, now at Michigan State University (MSU)] and **John Townshend** [then at UMD, now *Emeritus Professor*—shown in **Photo 2**, *right*], with the associated NASA Landsat data buys, which led to the creation of the Global Land Cover Facility (GLCF) at UMD and helped build the case for the Open Landsat Archive. In 1990 the International Geosphere–Biosphere Programme Data and Information System (IGBP-DIS) also led by John Townshend, made the science case for generating several global datasets, including the first 1-km Land Cover product in 1992. Townshend subsequently established the international Global Observation of Forest Cover and Land-use Dynamics (GOFC–GOLD) program as a pilot project for the **Committee on Earth Observation Satellites** (CEOS) in 1997, which continues to be supported by the LCLUC program.

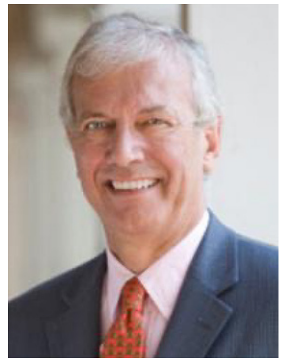


Photo 2. John Townshend played a prominent role in the early history of the LCLUC ST.

LCLUC STM Group Photos Through the Years

The annual group photo has become a tradition at many science team meetings; the LCLUC ST is no exception. Shown in this sidebar are three group photos taken throughout the past 25 years. The *top left* photo *below* was taken during the fourth LCLUC STM held in 2000 in Rockville, MD; the *top right* photo was taken during the eleventh LCLUC STM in 2006 at the University of Maryland, University College (now Global Campus) Inn and Conference Center in College Park, MD; and the *bottom* photo was taken during the recent twenty-fifth anniversary meeting in Bethesda, MD.

Notice the circa 2000 projection technology that is visible in the top photo: an overhead and a slide projector in front of the participants and a screen in the background. While projection technology certainly has evolved over time—and the Team has gotten larger—the high-quality, cutting-edge science results presented at these meetings have remained constant through the past quarter century and—as the recent COVID pandemic reminded us—the camaraderie among colleagues gathered in person to exchange information and ideas is hard to replicate.

Photo of the 2000 LCLUC STM participants. Note the circa 2000 projection technology in the room. **Photo credit:** Chris Justice/UMD

Photo of the 2006 LCLUC STM participants. **Photo credit:** Chris Justice/UMD

Photo of the 2022–23 LCLUC STM and "Silver Jubilee" participants. The group keeps getting larger. **Photo credit:** University of Maryland, College Park (UMD) Team

In 1994 the International Geosphere Biosphere Programme (IGBP) and the International Human Dimensions Programme (IHDP) officially launched the first joint Core Project on Land-Use and -Cover Change (LUCC), with David Skole as chair. The project focused on integrative land-use science from global analysis to local case studies. LUCC was the first Core Project involving both physical and social scientists and helped make the case for an innovative NASA science program, emphasizing the use of satellite observations.

An Early LCLUC Program Success Story: Landsat-Based Mid-Decadal Global Land Survey

The LCLUC program's initial success with global datasets was the creation of the Landsat-based Mid-Decadal Global Land Survey (GLS) dataset in 2005 in partnership with U.S. Geological Survey (USGS). This dataset was developed in response to the Landsat-7 Scan Line Corrector failure in mid-2003, which made the data less useful due to dropout lines on the sides of each image. A team of over 30 researchers proposed various gap-filling methods based on interpolation and compositing using adjacent or multiemporal coverage. The resulting methods, however, often had residual artifacts in the areas with high surface and atmospheric variability. Combining Landsat-7 and Landsat-5 data mitigated the problem of data gaps in each satellite collection. As a result, global, cloud-free, and geocorrected GLS datasets were produced for 2005 and 2010, while the datasets for 1975, 1990, and 2000, which had been generated previously, were reprocessed with better, updated corrections. Thus, 30-m (98-ft) global mosaics were created using one scene per epoch at the peak of the vegetation growing season, and became available for download at USGS—free of charge. At a time when Landsat data were not free and purchasing global Landsat time series was unaffordable for most university researchers, the GLS datasets played a key role in monitoring changes in urban, forest, and agricultural sectors. For example **Figure 1** (*right*) shows how the GLS data were used to track fire damage in central Canada.

Building on the success of GLS, the LCLUC program has funded the development of several other global data products over the last 15 years from Landsat observations, e.g., tree-cover extent, forest loss and gain, mangrove extent, cropland extent and change, and impervious surfaces. These products have provided the scientific foundation for research and societal benefit applications, and along with the Earth Science Technology Office's (ESTO) **Sustainable Land Imaging Technology** (SILT) program, insights for the design of future Landsat missions.

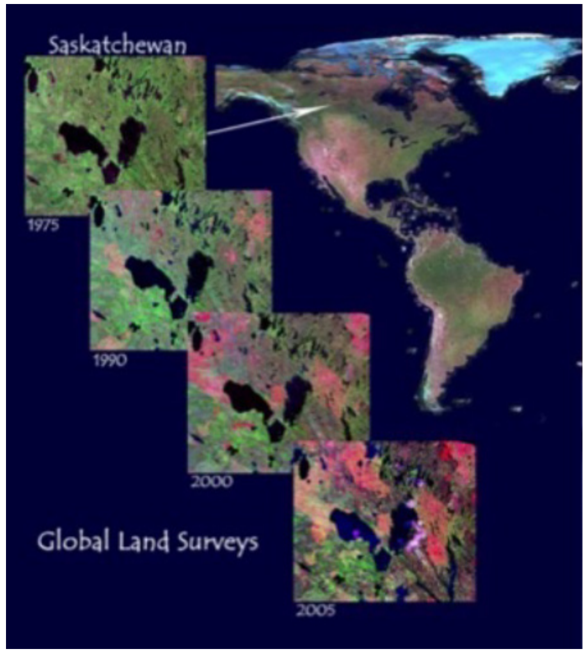


Figure 1. Inset images show the progression of burn scars in the province of Saskatchewan in Canada from the mid-1970s (*top left*) to mid-2000s (*bottom right*) derived from the multidecadal Global Land Survey data set, based on global, cloud-free, geocorrected Landsat 5- and 7 data, with the background red-green-blue composite of North and South America. **Note:** This image appeared on the cover of a 2008 issue of *Photogrammetry and Remote Sensing* [**Volume 74**, **Issue 1**] which contained an article describing the 2005 GLS by Garik Gutman, et al. **Figure credit:** Garik Gutman/NASA

The Present State of the LCLUC Program

The NASA LCLUC program is now part of the **Earth Science Carbon Cycle and Ecosystems research focus area**. Over the past 25 years it has funded over 300 projects involving more than 800 researchers, leading to over 1000 publications. The program has several components, which can be grouped into three themes: detection and monitoring; impacts and consequences; and drivers, modeling, and synthesis—with about one-third of the total number of studies contributed by each component, integrating biophysical, socioeconomic, and remote sensing sciences. The annual LCLUC ST meetings bring researchers together to discuss the latest LCLUC methods and data, present their findings, build collaborations, and provide program feedback. The program also has funded several international regional science initiatives such as Southern Africa Fire Atmosphere Research Initiative (SAFARI), Large Scale Biosphere Atmosphere Experiment in Amazonia (LBA), Northern Eurasia Earth Science Partnership Initiative (NEESPI), Monsoon Asia Integrated Regional Study (MAIRS), and South/Southeast Asia Research Initiative (SARI), engaging with regional scientists to further land-use science. More information about these initiatives can be found on the **LCLUC website**.

The LCLUC program interacts with national agencies, including USGS, U.S. Department of Agriculture (USDA), U.S. Agency for International Development (USAID), and programs such as the U.S. Global Change Research Program (USGCRP). The LCLUC Program's international partners include the GOFC-GOLD program, the Global Land Program (GLP), and the European Association of Remote Sensing Laboratories (EARSeL) Special Interest Group on Land Use and Land Cover.

The NASA LCLUC program aligns its programmatic activities with the agenda of the CEOS Global Earth Observations and the Group on Earth Observations (GEO), and develops close relations with space agencies worldwide. Outreach activities are carried out through e-newsletters, social media, and regular webinars. The **LCLUC website** has rich content, with meeting lists, webinars, projects, publications, and news on datasets and missions. In addition, the website also includes a "Mapper" tool that allows anyone to find information on past and ongoing projects. There are three maps at the bottom of the LCLUC homepage that show the **geographic areas of research**, the **location of research team members**, and the **geographic distribution of hotspots**.The program is involved in various capacity-building and training activities, internationally.

DAY ONE

The first day began with opening remarks to place this anniversary meeting in perspective. The remainder of the afternoon's agenda consisted of presentations on the Urban theme and LCLUC regional research programs. In the evening, the Silver Jubilee social celebration—see *LCLUC Silver Jubilee Celebration and Poster Session* on page 13—was accompanied by a poster session.

Garik Gutman [NASA HQ—*LCLUC Program Manager*] gave a welcome address and presented the **achievements of the LCLUC program** during the past quarter of a century. He included honorable mentions (i.e., names and photos) of those involved in the Program's success over the last 25 years—including most of the people who are called out in the introductory sections of this article.

Billie Turner [Arizona State University] described the evolution of the LCLUC program from the IGBP/IHDP LUCC Programme (1994 to 2015), which was designed to address the question: *How do human and biophysical forces affect changes in land use and, hence, land cover, and what are the environmental and social impacts of these changes?* Using satellite-based observations to study human–environment interactions, land use, and management were highlighted in the book *People and Pixels: Linking Remote Sensing and Social Science*, published in 1998, with chapters contributed by a number of LCLUC scientists. Several high-quality journal research articles in *Nature*, *Science*, and *Proceedings of the National Academy of Sciences* (PNAS) followed, reinforcing the need for LCLUC research and impact studies. Over the past 25 years the NASA LCLUC program has been integrating Earth observations in LCLUC studies to address the impacts of change on the environment and people. Some of the recently funded areas of LCLUC research include rural outmigration, societal conflicts, women's health, wildfire impacts, and the impact of the impact of land use and narcotrafficking on property values.

Ariane de Bremond [UMD] presented on the **Global Land Programme** (GLP) a global network promoting land-use science to address sustainable development of human–environmental land systems. GLP has over 2250 members across 110 countries and is divided into 12 working groups. Its program office moved from Switzerland to the U.S. in early 2023. Sustainable land systems are an integral part of sustainable development. "Smart" land use has the aim of securing farmers' livelihoods, promoting sustainable food production, eradicating poverty and inequality, and making urbanization sustainable. GLP facilitates synthesis studies in land-system science to inform science-based land policy. The GLP's 2023–2027 Science Plan aims to characterize land-system temporal dynamics and patterns, understand people's goals and priorities, and build pathways to transform and innovate through systemic interplays and adaptive learning. Bremond highlighted GLP–LCLUC cooperation by bringing together international experts in remote sensing and socio-economic science to address land monitoring and sustainability issues.

Tim Newman [USGS] provided a review and updates on the LCLUC-related USGS collaborative activities. The USGS National Land Imaging (NLI) program funds Landsat development and operations, applied sciences and applications, remote sensing research and development, national civil application activities, and national land remote sensing education and outreach grants.The USGS produces foundational products on U.S. land-cover and landscape change, which are well validated and serve as the "gold standard" for moderate-resolution land cover. The agency partners with federal, commercial, and international organizations to provide products for societal benefit, including fractional snow-covered area, burned areas, and dynamic surface-water extent. The National Land Cover Database, generated as part of the Multi-Resolution Land Characteristics consortium, provides consistent land-cover information for science, modeling, and land-management applications. USGS products are widely used for policy, assessing environmental impact, restoring ecologies, modeling habitats, and more. The USGS has been the steward of the Landsat program, which will continue with the **Landsat Next** mission to be launched in late 2030. Landsat Next will offer improved spectral bands, resolution, and coverage. (See "Missions, Data, and Products" section below for more discussion of Landsat.)

Nancy Searby [NASA HQ] presented information about NASA's **Applied Sciences' Capacity Building Program**, which provides workforce development, training, and collaborative projects to increase understanding Earth observations and their use globally. The program has three subprograms: the Applied Remote Sensing Training (ARSET) program, which offers virtual and in-person training on satellite remote sensing topics to help individuals and institutions integrate Earth observations into decision-making activities worldwide; DEVELOP, which provides early-career researchers with interdisciplinary, 10-week feasibility study experiences that apply NASA Earth observations to environmental issues; and SERVIR[2], which is a partnership between NASA and USAID that helps developing countries use satellite data to address critical challenges and develop innovative solutions to improve livelihoods and foster self-reliance. A new pilot project was recently launched, focusing on the **Indigenous Peoples' Capacity Building**. The aim of this initiative is to build relationships across NASA and indigenous communities through place-based remote sensing training, community engagement, and coproduction of knowledge. The capacity-building team is also working with global and domestic networks and organizations to promote open data access and coordinate capacity-building activities based on users' needs.

Dan Brown [University of Washington] reviewed the current status and the future of land-use modeling based on remote sensing. He recounted his participation in a 2013 National Research Council study that identified five approaches useful for LCLUC science and policy applications: agent-based, economic, cellular, statistical, and machine learning models. Remote sensing-derived biophysical variables—e.g., land cover, vegetation, and soils—are valuable inputs for all these modeling approaches. Remote sensing and other spatial data are also useful in identifying relationships between spatial factors and agent decisions. Brown emphasized the need for advancements in process-based and structural approaches, including cross-scale integration of models, especially land-change models and Earth System models at local, regional, and global scales. In addition, behavioral models of land systems are gaining significance and provide alternatives to econometric, equilibrium-based, and top-down models.

Urban Land Use

Karen Seto [Yale University] described strategic directions in urban remote sensing. She explained that—to date—most studies on urban remote sensing have primarily included countries with high or upper-middle income levels using three or fewer time points, with a focus on urban expansion and interurban changes. While these studies have been useful, it is important to address the drivers of urban LCLUC, distinguish urban land use from land cover, and map urban extent and expansion. Income levels and city sizes, especially in the Global South, are increasing, and there are highly dynamic urban changes with intra- and interurban variability in structure and composition, including three-dimensional (3D) volume—particularly important as Seto noted that few remote sensing studies have addressed the volume aspect. However, such characterization is extremely important as it can represent economic activities, e.g., the number of people or employees per square kilometer in high-rise buildings. She also emphasized the importance of connecting urban science to economic, environmental, and social issues, and to inform policies relevant to these topics.

After her presentation, Karen Seto moderated a panel on challenges in urban LCLUC science. Panelists included **Peilei Fan** [MSU], **Jody Vogeler** [Colorado State University], **Yufang Jin** [University of California, Davis], **Kirsten de Beurs** [Wageningen University], and **Alexey Shiklomanov** [NASA's Goddard Space Flight Center (GSFC)]. The panelists recommended integrating high-resolution satellite data and data from Google Street images, drones, and citizen science crowd-sourcing using data fusion approaches to characterize and map heterogeneity in urban environments. They emphasized the need for integrated modeling approaches using machine learning and artificial intelligence to address coupled human–natural systems problems related to urbanization and its socio-economic consequences. Ground-based data should also be integrated with maps to aid decision making across diverse scales.

Regional Programs

Michael Keller [U.S. Forest Service (USFS)] provided reflections on the **Large-Scale Biosphere-Atmosphere Experiment in Amazonia** (LBA) regional Amazon initiative. LBA was primarily based on a partnership between NASA and the Brazilian Space Aeency [Instituto Nacional de Pesquisas Espaciais (INPE)], with collaborations at the principal investigator, institutional, and intergovernmental levels. The initiative focused on research, training, and education, aimed to answer questions about how Amazonia functions as a regional entity and how changes in land use and climate affect its biological, chemical, and physical processes. LBA researchers found that cattle ranching and agriculture in Amazonia were driven by market incentives rather than subsidies, and that from 1978–2002 secondary-forest area had increased fivefold. Fire poses a significant threat to the integrity of Amazon forests,

[2] SERVIR is not an acronym. It's a Spanish word that means "to serve."

with climate oscillations and economic changes affecting seasonal fire activity. LBA researchers found that public policies can help reduce or increase tropical deforestation, and that smallholder deforestation in colonization frontiers is associated with family size, life history, and market access.

Pasha Groisman [National Oceanic and Atmospheric Administration (NOAA)] presented information on the **Northern Eurasia Earth Science Partnership Initiative (**NEESPI), an interdisciplinary program aimed at understanding the interactions between the terrestrial ecosystem, atmosphere, and human dynamics in Northern Eurasia. The program was launched in 2004 and included more than 170 projects with over 750 scientists from more than 30 countries. NEESPI grew out of informal discussions at various meetings and conferences over several years between U.S., Russian, and European scientists. NASA and the Russian Academy of Science (RAS) had a prior history of collaboration (from the early 1990s through the early 2000s), which provided the basis for establishing a plan for a major Northern Eurasia-wide scientific project. The plan included NASA and other U.S. agencies, RAS, and multiple international, non-Russian partners. NASA made major contributions in funding NEESPI from its inception to its synthesis stage, which enabled its evolution and success. NEESPI resulted in greater cooperation and more integrated studies between the participants—including the publication of 1400 papers and 36 books.

In 2016 NEESPI transitioned into the Northern Eurasia Future Initiative (NEFI) under the Future Earth program with a focus on sustainable development under changing climate, ecosystems, and society. NASA continues its support by funding research teams working on LCLUC in Eastern Europe, the Caucasus, and Central Asia. NEFI uses regional models, Earth system models, and integrated assessment models to project possible futures under different scenarios of environmental changes and socio-economic conditions in Northern Eurasia.

Krishna Vadrevu [NASA's Marshall Space Flight Center (MSFC)] summarized the accomplishments of the **NASA South/Southeast Asia Research Initiative** (SARI). He highlighted various activities and studies carried out under SARI since its inception, including regional meetings, capacity-building training, publications, collaborations, solicitations, and field visits. Since the first SARI solicitation (ROSES[3]-2015), over 25 projects have been funded by the LCLUC program, involving more than 300 U.S. and international scientists from over 190 organizations. Nearly 300 papers have been published in peer-reviewed journals, four books (with a fifth in press), and 14 different journal special issues produced through SARI collaborations. Regional meetings involving space agencies, governmental and nongovernmental organizations, local universities, students, and professionals have helped U.S. scientists develop a wide range of international collaborations, useful for testing several NASA satellite datasets and novel algorithms, and sharing science results and information with local decision makers. The SARI program organizes capacity-building and training events in developing countries to train young researchers on novel remote sensing and geospatial technologies and tools for research and applications. Three synthesis projects have recently started—one on South Asia and two on Southeast Asia—that will synthesize not only the SARI-funded projects but also other important international and national projects in the region.

DAY TWO

The second day featured presentations that focused on two important themes: Agriculture, Forests, and Other Land Use (AFOLU); and Fires.

Agriculture, Forests and Other Land Use

Matt Hansen [UMD] presented the **Global Land Analysis and Discovery** (GLAD) team activities. The primary focus of GLAD is to investigate the methods, causes, and impacts of global land-surface change using Earth observation imagery as the primary data source. GLAD has generated various products, including an alert system implemented in collaboration with Google and World Resources Institute as part of **Global Forest Watch**. In addition to providing global, timely alerts of forest change, this system produces an annual update based on a calendar year, which was first prototyped using Landsat 7 data from 2000–2012 and has been updated annually.

David Skole [MSU] highlighted the remote sensing and policy aspects of AFOLU landscapes. These landscapes are crucial not only for carbon sequestration but also for mitigation and adaptation actions. Trees Outside Forests (TOF) systems are an important component of AFOLU, especially in developing countries and the tropics—see **Figure 2** on page 19—and include sparsely treed ecosystems, agroforestry, and other tree-based production systems. National-scale, individual-tree carbon-mapping projects are now feasible by integrating high-resolution satellite data and deep-learning algorithms. Focusing on AFOLU and TOF can help achieve net-zero carbon goals by adding

[3] ROSES stands for Research Opportunities in Space and Earth Science. This is an omnibus funding apparatus for NASA research.

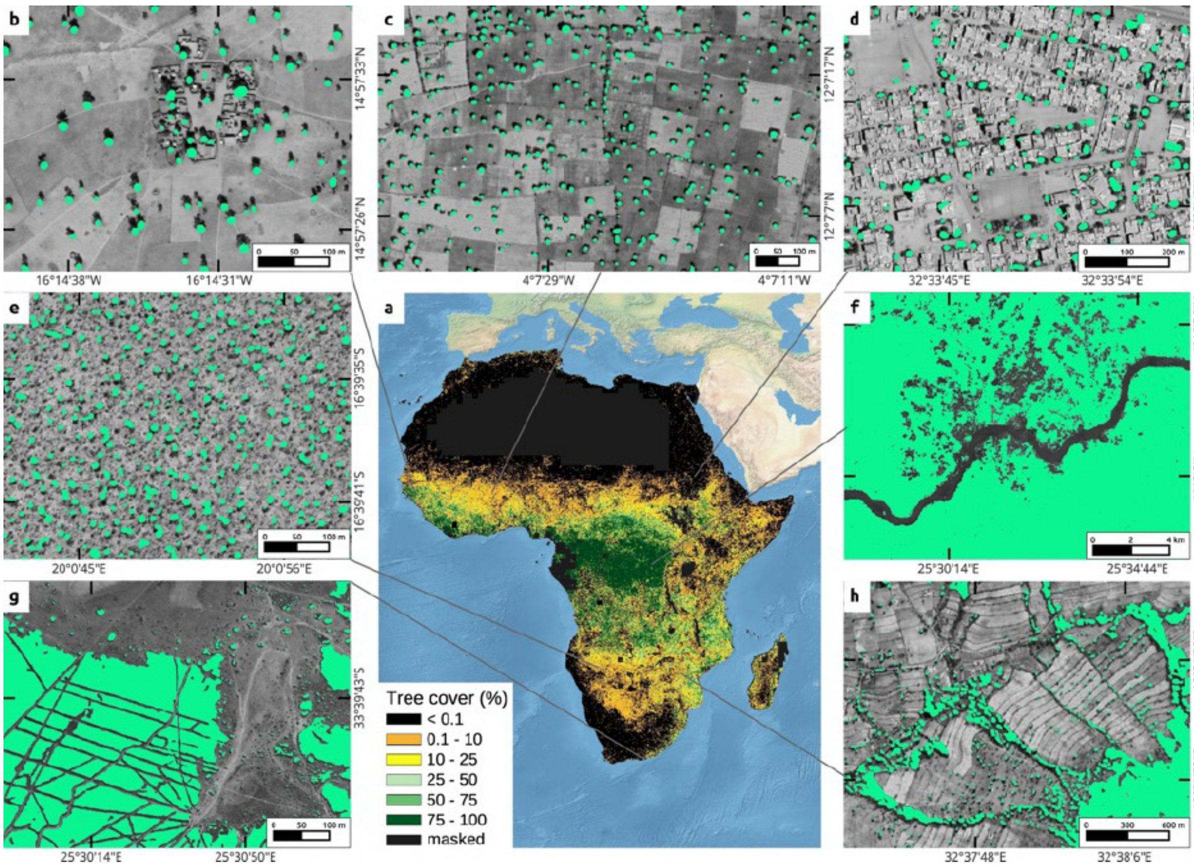


Figure 2. Mapped tree cover across areas of different tree densities in Africa. Shown here is the percentage of tree cover, at 1 km (0.6 mi) spatial resolution [*center*]; and several examples of predicted tree cover overlaid on Google Maps satellite imagery, each referenced on the center map of Africa. These include: a village in Senegal [*top row, left*]; agricultural fields in Burkina Faso [*top row, center*]; an urban environment in Khartoum, Sudan [*top row, right*]; Miombo woodlands in Angola [*middle row, left*]; deforestation in the Democratic Republic of Congo (DRC) [*middle row, right*]; Eucalyptus plantations in South Africa [*bottom row, left*]; and terrace farming in Zimbabwe [*bottom row, right*]. **Figure credit:** David Skole/ Michigan State University—from a **2023 article in Nature Communications**; Google map images ©2022 CNES/Airbus, Landsat /Copernicus, Maxar Technologies, Map data ©2022

landscapes in Africa, Asia, and Latin America,[4] with potential for atmospheric carbon removal, enhancing adaptation and livelihoods, and generating stable income under climate-stress conditions.

Martin Herold [Helmholtz Center, Potsdam, *Germany*] provided updates on the GOFC–GOLD and Global Forest Observations Initiative (GFOI) activities. The GOFC–GOLD Land-Cover office—previously based at Wageningen University in the Netherlands—relocated to the Helmholtz Centre in 2021. The office provides input on land cover to the World Meteorological Organization's Global Climate Observing System (WMO-GCOS) essential climate variables and promotes community consensus guidance and standards to international **Reducing Emissions from Deforestation and Forest Degradation** (REDD+) Programme, including conservation, sustainably managing forests, and enhancing forest carbon stocks, as well as the UN Sustainable Development Goals (SDGs). The office also supports international space agencies and global land-monitoring programs for user needs, standards, and validation, and provides outreach support and capacity development through GOFC–GOLD Regional Networks. GOFC–GOLD activities are undertaken in partnership with GFOI, which involves a global land-cover comparison and validation exercise with various land-cover products. The key issues for GOFC–GOLD in the coming years include continuing its convening role in promoting Earth observations (EO) of land-cover activities, providing guidance on calibration and validation protocols, conducting inter-comparison exercises of land-cover products, building capacity and training, addressing AFOLU issues, and enhancing the transparency and speed of access to actionable information to inform effective land-use policies.

Ruth DeFries [Columbia University] moderated a panel that discussed challenges in the forestry sector. Panelists included **Sean Healey** [USFS], **Alexandra Tyukavina** [UMD], **Christoph Nolte** [Boston

[4] To reach net-zero carbon goals, one approach is to prioritize emissions inventories from AFOLU activities and carbon sequestration from TOF initiatives. It is crucial to focus on AFOLU and TOF projects in the landscapes of Africa, Asia, and Latin America, as the outcomes have significant implications for atmospheric carbon removal, adaptation and livelihood enhancement, and the generation of stable income during climate-stressed conditions.

University], and **Randolph Wynne** [Virginia Tech]. The discussion emphasized the importance of understanding the climate effects on forest carbon sequestration (e.g., albedo effects). Forests are darker than other land-cover classes and absorb relatively more solar radiation, which may cause local warming. Therefore, when accounting for carbon the influence of albedo should be considered. Ensemble-based methods can considerably improve spatial and temporal accuracy in detecting forest loss and gain for forest change detection analysis, rather than using a single algorithm. It is also important to map the world's trees at fine spatial and temporal resolutions, which requires high-spatial-resolution data and tree-height observations from lidar.

Brad Doorn [NASA HQ] gave a presentation on applied science aspects of land use in **NASA's Agriculture and Water Resources Applications Program**. The Water Resources program is discovering and demonstrating new practical uses for NASA's EO in the water resources management community, while the Western Water Applications Office (WWAO)'s goal is to integrate NASA Earth observations into decision-making processes.

Chris Justice discussed the **NASA Harvest** program, a consortium of about 50 partners, led by **Inbal Becker-Reshef** [UMD]. The Harvest program is addressing food security, agricultural resilience, and markets and trade, working directly with stakeholders to develop EO-based analytics and tools that inform decisions and improve understanding of our global agricultural systems. Researchers from Harvest partner with national governments, humanitarian organizations, and policymakers to provide timely, accurate, and actionable information to prepare for and respond to food-related challenges. The Harvest program benefits from underpinning research developed in the LCLUC program. Justice also described **NASA Acres**, a newly competed agricultural consortium led by **Alyssa Whitcraft** [UMD]. NASA Acres focuses on applying EO information to challenges facing U.S. farmers, ranchers, and agrifood systems.

Alexander Prischepov [University of Copenhagen, *Denmark*] then gave a presentation on land abandonment. The study of farmland abandonment is crucial due to its significant implications on environmental processes—e.g., biodiversity, carbon sinks, invasive species encroachment, and the spread of wildfires—as well as effects on livelihoods. However, studying land abandonment is challenging because it involves a transition process as new land uses may emerge. There are clear benefits to characterizing land abandonment and its underlying processes, combining high-resolution data with time-series analysis. For instance, in South Sudan farmland abandonment is linked to armed conflicts and food insecurity.

Arnon Karnieli [Ben Gurion University, *Israel*] gave a presentation on droughts as potential triggers for the Syrian civil war, now in its eleventh year. Satellite data analysis revealed that climate-induced droughts were not the main cause of the country's political instability. Instead, the construction of dams along the upstream Turkey side of the Euphrates River resulted in significant water resource issues and agricultural losses in Syria.

Ranjeet John [University of South Dakota] discussed the status and future of remote sensing of rangelands. Rangelands around the world are experiencing varying degrees of land degradation; remote sensing can be used to monitor their status. Vegetation indices derived from remote sensing are strongly correlated with above-ground biomass in rangelands—but ground-truth data are needed for better product accuracy. The **Rangeland Condition Monitoring Assessment and Projection** (RCMAP) product suite provides excellent data on rangelands in the Western U.S., including eight fractional components *and rule-based error maps*—a type of error-detection system for data analysis. These data cover a period of 36 years (1985–2021) and provide change information for each year.

Following these presentations, **Meha Jain** [University of Michigan] moderated a panel on Challenges in Agricultural Remote Sensing and Land-Use Change. Panelists included **Kaiyu Guan** [University of Illinois Urbana-Champaign], **Sergii Skakun** [UMD], **Martha Anderson** [USDA's Agricultural Research Service], and **Xiao-peng Song** [UMD]. The discussion focused on the importance of mapping not only crop type and yield in near-real time and over the long term but also management practices, e.g., cover cropping, crop rotations, and tillage. Additionally, mapping evapotranspiration is important to address challenges related to drought and climate.

Fires

Louis Giglio [UMD] gave an overview of NASA fire products; **David Roy** [MSU] addressed the future of fire monitoring; and **Michael Falkowski** [NASA HQ] described the new **NASA FireSense Program**.[5] The presentations highlighted the need to generate high-resolution fire products and harmonized Landsat –Sentinel-2 burned-area products at regional-to-global scales thoroughly validate new fire products, restore and retain the original "extended" missions for NASA's Terra and Aqua platforms, and to support long-term fire data assessment and harmonization. A dedicated active-fire and fire radiative power (FRP) wildfire satellite constellation is needed for robust

[5] To learn more about FireSense and the burned area and active fire products, see "**Summary of Fifth Joint GWIS/GOFC–GOLD Science Team Meeting**," in the September–October 2022 issue of *The Earth Observer* [**Volume 34**, **Issue 5**, pp. 12–20].

mapping of fires at very high spatial and temporal resolutions. It is also important to coordinate the calibration of visible/near infrared, middle infrared, and thermal bands for the various low-Earth-orbiting, fire-monitoring satellite constellations as well as for geostationary satellites, to enable scientific use of the data. In addition to detection and monitoring, research on fire-related LCLUC issues—including impacts on the environment—need to be considered.

After the fire presentations, **Krishna Vadrevu** moderated a panel discussion on the challenges in fire monitoring and land-use science. Panelists included **Volker Radeloff** [University of Wisconsin–Madison], **Luigi Boschetti** [University of Idaho], **Mark Cochrane** [UMD, Center for Environmental Science], and **Joanne Hall** [UMD]. The panel identified several needs and challenges related to fire monitoring and land-use science. These include generating harmonized burned-area products at regional-to-global scales, validating new products, and filling gaps in active fire data when the **Moderate Resolution Imaging Spectroradiometer** (MODIS) data from Terra platform are discontinued. There is also a need for a long-term pre-MODIS burned-area record and a dedicated active fire and FRP wildfire constellation for robust mapping of fires. The panelists emphasized the importance of addressing fire-LCLUC issues and characterizing fire risk at the wildland–urban interface. Additionally, physics-based definitions are needed for terms, such as fire severity and risk, and characterizing small fires remains a challenge. Finally, integrating top-down and bottom-up approaches and promoting communication, collaboration, and coordination among data producers and users are crucial activities to successfully manage fires.

DAY THREE

The third and final day of the meeting included presentations on international partner programs, missions, data and product overviews, and future directions for the LCLUC program.

International Programs

Benjamin Koetz [European Space Agency (ESA)] presented an update on ESA's satellite missions. He reported that there are currently 14 operational satellites in orbit, 6 heritage satellites, 40 satellites in development, and 20 being prepared. Koetz explained that a major part of ESA's Earth observing fleet are the **Copernicus Sentinel missions**. In July 2022 the Sentinel-1B mission officially ended—with detailed investigations into a power system anomaly in December 2021. Sentinel-1A remains operational—although it has already exceeded its design life of seven years—and the launch of Sentinel-1C is planned for the second quarter of 2023. Collection 1 of the Sentinel-2 data will be delivered through the Copernicus Data and Information Access Services (DIAS) platforms, including Level-1C (L1C) and L2A products. He also discussed the **Sentinel Expansion missions**, which include Copernicus Anthropogenic Carbon Dioxide Monitoring (CO2M), Copernicus Hyperspectral Imaging Mission for the Environment (CHIME), Copernicus Imaging Microwave Radiometer (CIMR) to monitor the sea surface, Copernicus Land Surface Temperature Monitoring (LSTM), Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) for climate change effects, and Copernicus Radar Observation for Europe in L-band (ROSE-L) for forest management and agricultural applications.

Ioannis Manakos [Centre for Research and Technology, *Greece*] presented an overview of European research directions in land-use science. The management of rural land in Europe affects the environment and social fabric of much of rural Europe, with agriculture being a major driver of land-use and management decisions. Agriculture and other land uses contribute around 23% of global greenhouse gas emissions in Europe, and using land as a carbon sink to offset emissions from other sectors is challenging due to inaccurate accounting. The presentation emphasized the need for a consensus approach, expanded calibration and validation, field data integration, and involving local expertise for describing land-cover/habitat ecosystem classes. The new European Union regulation on Land Use, Land-Use Change and Forestry (LULUCF) establishes a new governance process for monitoring how member states calculate emissions and removals from actions in their forests.

Missions, Data, and Products

Kerry Cawse-Nicholson, also representing her collaborator **Simon Hook** [both from NASA Jet Propulsion Laboratory (JPL)] gave an update on NASA's **ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station** (ECOSTRESS) mission, which measures land surface temperatures from the International Space Station (ISS). ECOSTRESS is capable of detecting and monitoring environmental events such as wildfires, volcanic eruptions, urban heat, and plant stress. ECOSTRESS provides frequent and high-resolution measurements, enabling accurate monitoring and decision-making for water resource managers, urban planners, and fire-resource allocations.

Chris Neigh [GSFC—*Landsat Project Scientist*] provided an update on the joint NASA–USGS **Landsat program**, which celebrated its fiftieth anniversary in 2022 at various meetings throughout the year—e.g., Pecora 2022.[6] Neigh reported that systems are nominal for Landsat 8 and Landsat 9. Landsat 9 radiometric

[6] To learn more, see "**NASA Participates in Pecora 22 Symposium and Celebrates Landsat 50th Anniversary**," in the November–December 2022 issue of *The Earth Observer* [**Volume 34**, **Issue 6**, pp. 4–9].

and geometric performance is excellent from a calibration/validation (cal/val) perspective. Landsat 9 Thermal Infrared Sensor–2 (TIRS-2) radiometric and geometric performance has significantly improved when compared to Landsat 8 TIRS. Landsat 7, launched in 1999, is still active and has taken over 2.8 million images of Earth that have been added to the global Landsat archive. Landsat 7 was running at approximately 450 scenes per day and downlinking them to sites around the world. Over the years, Landsat 7 has suffered a few component issues, but considering its advanced age (almost 23 years old), it has held up extremely well. The forthcoming **Landsat Next** will have improved revisit frequency, higher spatial resolution, and additional spectral bands, all maintaining the radiometric quality.

Ralph Dubayah [UMD—**Global Ecosystem Dynamics Investigation** *(GEDI) Principal Investigator*] presented details on GEDI, which is a joint project between the University of Maryland and GSFC. It has been operational on the ISS since April 2019 and uses lidar waveforms to provide ground elevation, canopy height, cover, and various profiles and metrics. GEDI uses three lasers to produce eight transects of lidar waveforms, with each footprint providing the complete vertical structure of the canopy. GEDI estimates total global biomass to be 30% more than reported by the United Nations' Food and Agriculture Organization (FAO). The GEDI data have been downloaded over 1.5 million times from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). As an example of GEDI data use, **Peter Potapov** [UMD] and the GLAD team have integrated GEDI forest structure measurements and Landsat analysis-ready time-series data to map canopy height globally—see **Figure 3** below. Although GEDI is operating well, it has exceeded its planned time allocation on the ISS. The current plan is to temporarily move GEDI to an alternate location on the ISS, where it will remain offline for about 18 months, while a U.S. Department of Defense (DOD) technology payload completes its mission.[7] In 2024 GEDI will return to its original location and hopefully resume operations through the remaining life of the ISS.

Kyle McDonald [JPL] and **Gerald Bawden** [NASA HQ] described the joint **NASA–Indian Space Research Organisation (ISRO) Sythetic Aperture Radar** [NISAR] mission, which is planned for launch in 2024. NISAR will use two different radar frequencies to systematically map Earth's surface every twelve days—measuring changes as small as a centimeter. The data will be delivered through the JPL DAAC with different processing levels and will help to determine surface properties.[8]

Garik Gutman provided updates on the **Multisource Land Imaging** (MuSLI) and **Harmonized Landsat-Sentinel** (HLS) datasets. MuSLI projects aim to develop algorithms and prototype products using multiple satellite sources, including international and commercial data. MuSLI's first solicitation for funding was released in 2014, and the funded projects successfully developed new and improved land products via multisource data. The U.S. researchers gained knowledge and experience with Copernicus sensors and datasets. The MuSLI team was able to provide feedback to ESA on data quality and usability issues, geolocation errors, product formats (e.g., filenames, granule organization), including the importance of reprocessing and collections. The projects helped improve collaboration

[7] **UPDATE:** As of publication of this issue, GEDI has been moved into "storage," where it will remain until 2024.
[8] **UPDATE:** The NISAR science payload, consisting of two radar systems, recently arrived at ISRO's facility in Bengaluru, India, where it will be combined with the satellite's body and tested before its three-year mission.

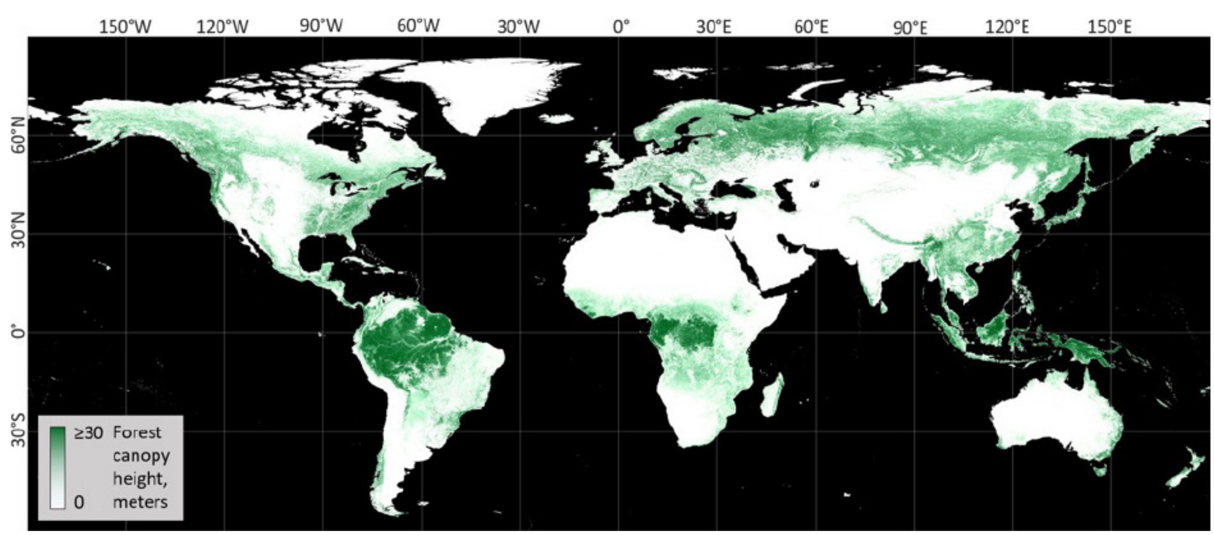


Figure 3. Data from NASA's GEDI lidar have been combined with Landsat 8 "analysis-ready" data to create this map of global forest canopy height for 2019. The taller the forest, the darker the shade of green on the map. **Note:** Image taken from a **2020 article in Remote Sensing** [**Volume 12**, **Issue 3**] by Potapov et al. (2020). **Figure credit:** GLAD Team/UMD

with international researchers as they serve as co-investigators on MuSLI Projects. The Sentinel-2 HLS project is an extension of research conducted at GSFC, which takes data from the Landsat 8 and 9 and the Sentinel-2A and -2B satellites to generate a harmonized, analysis-ready, surface-reflectance data product, with observations about every three days.

Future plans for HLS include integration of Sentinel-2C data, enhancements with new bidirectional reflectance distribution function (BRDF) correction, bandpass adjustment, and topographic reflectance correction for mountainous areas.

Will McCarty [NASA HQ] discussed the NASA **Commercial Smallsat Data Acquisition Program** (CSDA). The CSDA pilot was launched in 2017 to assess data from small-satellite constellations for research and applied science activities. In 2018 Blanket Purchase Agreements (BPAs) were awarded to Maxar (DigitalGlobe) Inc., Planet Labs Inc., and Spire Global. The pilot program concluded in 2020 but the program has been sustained. The CSDA Program aims to establish a process to bring onboard new commercial data vendors for sustained use of purchased data for broader use and dissemination by the Earth science community. The program's objectives include long-term data preservation, access, distribution, and scientific reproducibility. New vendors are becoming part of the CSDA activities (e.g., Airbus, Blacksky Geospatial Solutions, Capella Space, ICEYE US, GeoOptics, and GHGSat). CSDA data holdings will be available via **Earthdata Cloud Search** for Calendar Year 2022.

Kerry Cawse-Nicholson presented details on coordination and calibration aspects of thermal infrared instruments planned for three upcoming missions including: the French [Centre Nationale d' Études Spatiale (CNES)]–Indian [ISRO] **Thermal Infrared Sensor for High-Resolution Natural Resource Assessment** (TRISHNA) mission, NASA's **Surface Biology and Geology** (SBG) mission (planned as part of NASA's **Earth System Observatory**), and ESA's Sentinel **Land Surface Temperature Monitoring** (LSTM) mission. These sensors are planned for launch in 2025, 2027, and 2029, respectively, allowing for a continuous record and daily coverage of thermal remote sensing data. The JPL team is developing a suite of sites with necessary instrumentation to calibrate and validate the data and products from these thermal instruments. They are also working on algorithms, calibration, and validation approaches to generate common products across missions and conducting joint airborne campaigns to prototype datasets and evaluate algorithms.

Future Directions of the Program

After spending three days reviewing the history of the LCLUC program and assessing its current state, **Chris Justice** provided some thoughts from the program management team on future directions for the program. He started by saying that land-use change involves human decision making and, in that context, LCLUC research is inherently societally relevant. Looking forward to the next 25 years, he emphasized the significance of tackling climate change and its effects on land use, pointing out that the land-use aspects of both mitigation and adaptation are something that humans can, in principle, manage. However, to be able to limit global temperature increase to 1.5 °C (2.7 °F), it is essential to take climate mitigation measures *now*—including those discussed at this meeting related to agriculture, forestry, and other land use—as the impacts of climate change (e.g., heatwaves, fires, floods) will likely continue to worsen. To mitigate these risks, adaptation and mitigation measures related to land use are crucial, and international cooperation will be needed to address these global challenges. With the world population projected to reach 9.8 billion by 2050, there will be an increased demand for water and food security, and natural resources will become scarcer, making a transition to green energy necessary. Land-use and -management research will play a central role in informing the necessary policies and management solutions.

Going forward, the LCLUC program plans to build on its current research areas related to land-use science. These include land-use and -management characterization for forests, agriculture and urban environments; characterizing changing fire regimes; and studying the impacts of extreme weather, conflicts, pandemics, and natural disasters on land use. The program will explore the relationship between land use and climate mitigation and adaptation, as well as AFOLU emissions. Additionally, the program will continue to work on resolving issues related to characterizing land-cover and land-use change—e.g., more nuanced definitions of land abandonment and fallow land. In the future, the LCLUC program expects to continue to make advances in remote sensing, including continued development of data fusion methods with the MuSLI project, incorporating data from the sensors onboard the ISS (ECOSTRESS and GEDI), as well as **Ice, Cloud and land Elevation Satellite–2** (ICESat-2). There will be a near-term focus on infrared remote sensing in combination with optical and microwave sensor data and making operational very-high-spatial-resolution methods that would include using of artificial intelligence/machine learning for fine-scale monitoring. Another area of research is to integrate satellite data with models and ground observations, such as **Google Street View** or **Google Crop View**. The program will work on standardizing 3D urban satellite products (e.g., urban volume) using synthetic aperture radar (SAR), lidar, and stereo methods, as well as developing new capabilities in hyperspectral data for studying land use.

The LCLUC program will continue developing algorithms and datasets for land-use science. This includes extending the HLS data set to Landsat 9 and Sentinel-1 data, as well as developing product validation and accuracy assessment methods. There is a need to develop best practices and uncertainty assessment in these areas. A new study is underway to evaluate ESA's Sentinel-3 observations for active fire detection to replace the Terra MODIS mission—which is coming to the end of its planned life. Additional opportunities for LCLUC include research in preparation for upcoming missions, e.g., NASA's NISAR, SBG, Landsat Next missions, and ESA's Biomass, Fluorescence Explorer (Flex), CHIME, ROSE-L, LSTM, and TRISHNA missions, as well as the Copernicus Sentinel Continuity program, which aims to ensure continuity between the various Sentinels of one type

The LCLUC program is actively seeking partnerships to advance its research goals. The program needs additional funding for the underpinning science research to support NASA's growing applications programs in land-use research areas such as agriculture, fire, urban, and water management. There are also a number of opportunities for LCLUC scientists to contribute to other NASA programs, e.g., the **Inter-Disciplinary Science** (IDS), **Making Earth Science Data Records for Use in Research Environments** (MEaSUREs), and **Advanced Communications Capabilities for Exploration and Science Systems** (ACCESS) programs. The LCLUC program is also exploring technology development opportunities through NASA's **Earth Science Technology Office** (ESTO), including the development of sensor constellations, high-volume data processing, and contributing to developing the **Earth System Digital Twins**.

The LCLUC program would also like to identify opportunities for interagency cooperation, in response to higher-level directives, strengthening relationships with the USGS, USDA, and NOAA, as well as the interagency **Satellite Needs Working Group** (SNWG). By collaborating with these agencies and activities, the LCLUC program can better align its research with broader national priorities and strengthen its impact.

The LCLUC program will continue its partnerships with international organizations, including CEOS' **Land Product Validation (LPV) Subgroup** and Wildfire pilot project, and the AFOLU Stocktake initiative. The program will continue to collaborate with GOFC-GOLD to document best practices and build regional network capacity related to the use of NASA data and nationally determined contributions (NDCs). In the near term, LCLUC will work with the **Group on Earth Observations Global Agricultural Monitoring** (GEOGLAM) Initiative on cropland and crop type product validation, and with ESA on shared initiatives, such as the **Thematic Exploitation Platforms** (TEP). The program will also continue to collaborate with the **European Association of Remote Sensing Laboratories' Special Interest Groups on Land Use and Land Cover** (EARSAL SIG LULC) to advance research in the field. In conclusion, Justice said that all these future directions highlight the need for collaborative frameworks to address the LCLUC issues at local, regional, and global scales.

Meghavi Prashnani [UMD] and **Garik Gutman** provided updates on the **LCLUC website**, which contains information on a variety of topics—e.g., publications, data products, maps of LULUC project study areas, principal investigator (PI) information, new solicitations and selections, webinar presentations, and newsletters. They also provided guidance on how to join the LCLUC mailing list.

Conclusion

Coming full circle, **Garik Gutman**, who opened the meeting, delivered the concluding remarks. He expressed gratitude to all the researchers who had made significant contributions to the LCLUC program's success over the past 25 years. Gutman also recognized the researchers who have gained media attention and awards during the past couple of years.

The next LCLUC Science Team meeting is to be held May 8–9, 2023, in College Park, MD, in conjunction with the Joint Carbon Cycle and Ecosystems Focus Area Science Team meeting (May 10–12, 2023, in College Park, MD).[9] ■

[9] **UPDATE:** Both of these meetings have taken place and went well. A summary is planned for an upcoming issue of *The Earth Observer.*

Summary of the 2022 Precipitation Measurement Mission Science Team Meeting

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Introduction

The annual Precipitation Measurement Mission (PMM) Science Team Meeting (STM) took place October 3–7, 2022, in Denver, CO, as a hybrid meeting. The PMM program supports scientific research and applications, algorithm development, and ground-based validation activities for the Tropical Rainfall Measuring Mission (TRMM)[1] and Global Precipitation Measurement (GPM) mission—including the GPM Core Observatory (CO).[2] There were 134 attendees from NASA, the Japan Aerospace Exploration Agency (JAXA), the U.S. National Oceanic and Atmospheric Administration (NOAA), universities, and other partner agencies, including 19 attendees from 6 countries outside the U.S., of which 97 were present, and some of whom are shown in **Photo 1**, below. This is the first official in-person PMM STM since prior to the pandemic in 2019.

The meeting included general oral and poster sessions covering mission and program status, partner reports, GPM algorithm developments, and Science Team (ST) projects and activities, as well as thematically focused precipitation working group meetings held on the first and last days of the meeting. Note that the general sessions of the 2022 PMM STM departed from previous PMM STM practice: Given the large number of new principal investigators (PI) added to the PMM ST, the meeting began with 10-minute presentation updates on science projects from each ST member. This approach allowed the PMM ST as a whole to become acquainted with each other and to look for synergies and cross-fertilizations between new and existing teams and working groups. PIs were encouraged to create a poster to discuss their projects with members in more detail during the poster sessions. The general sessions of the meeting concluded with PMM programmatic updates and mission status from both the NASA and JAXA leads.

This article presents highlights from the 2022 PMM STM. The **meeting agenda** and **full presentations**[3] provide more details accounts of the items summarized herein.

[1] While the TRMM mission was completed in 2015, TRMM data reprocessing occurs whenever GPM data products are processed.

[2] TRMM and GPM are partnerships between NASA and the Japan Aerospace Exploration Agency (JAXA), with a Science Team that includes more than 20 additional international partners. To learn more about GPM, see **"GPM Core Observatory: Advancing Precipitation Measurements and Expanding Coverage"** in the November–December 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 6**, pp. 4-11] and **"The Global Precipitation Measurement (GPM) mission's scientific achievements and societal contributions: Reviewing four years of advanced rain and snow observations,"** in the *Quarterly Journal of the Royal Meteorological Society*, [**Volume 141**, **Issue 51**].

[3] NOTE: Access to the full presentations is password protected. The linked text goes to a contact form that must be filled out to be granted access.

Photo 1. Attendees of the 2022 PMM STM in Denver, CO. **Photo credit:** Chris Kidd/Goddard Space Flight Center (GSFC) and University of Maryland, College Park

PMM Programmatic and Mission Status Updates: Perspectives from NASA and JAXA

The PMM mission was launched February 27, 2014, on Japanese H-IIA rocket from the JAXA Tanegashima Space Center. Its components continue to function nominally—with continued developments reported on several fronts, including the GPM mission operations center, GPM core products, data acquisition, processing, archiving, and GPM applications and outreach activities. There were also reports from NASA Headquarters (HQ) on the future of precipitation science and the upcoming precipitation-related NASA mission, e.g.,the Atmosphere Observing System (AOS), which is one of the missions planned to be part of the Earth System Observatory.

NASA

Will McCarty [NASA Headquarters (HQ)—*GPM Program Scientist*] gave a perspective from NASA HQ. He emphasized that precipitation-related science is an important component of NASA's Earth Science goals. McCarty introduced several current and upcoming missions and programs, including satellite launches, such as the NASA Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) and Investigation of Convective Updrafts (INCUS); and field campaigns, including **Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms** (IMPACTS) and **NASA Convective Processes Experiment Cabo Verde** (CPEX-CV).

McCarty concluded with a discussion about the future of GPM, which is still the anticipated backbone for precipitation science until 2029. However, small satellites and commercial sources are expected to become an important additional source of information to address science questions over the next decade. Bridging these data acquisitions to other observational, assimilation, and modeling studies is fundamental to the advancement of precipitation science.

George Huffman [NASA's Goddard Space Flight Center (GSFC)—*GPM Project Scientist* and *PMM ST Lead*] provided an update on the GPM mission and instruments: the GPM Microwave Imager (GMI) radiometer and Dual Frequency Precipitation Radar (DPR). He introduced the status of the reaction wheels that help maintain flight attitude, as one of the five wheels has failed. He noted that the Mission Operations Center is currently developing a contingency plan in case of other wheel failures, however the mission can survive with only three functional reaction wheels. All other subsystems and instruments are all fully functional.

Huffman explained that the projected lifetime for GPM—based on fuel usage alone—is until 2029. However, the amount of solar activity has an impact on that calculation. The Sun is expected to be quite active over the next few years as we approach the Solar Maximum for Solar Cycle 25— which could shorten GPM's lifetime by as much as two years. He noted that a controlled reentry is planned—and enough fuel has to be kept in reserve to allow this to happen.

Huffman also discussed the status of the GPM data products. He reported that all GPM core data products are at Version 7 (V07). While the V07 Integrated Multi-Satellite Retrievals for GPM (IMERG) algorithm is completed, there are still minor calibration issues in the TRMM-era data to be resolved. He ended by noting that the **NASA Precipitation Processing System** (PPS) does the heavy lifting for project computing for core products, while the Goddard Earth Sciences Data and Information Services Center (GES DISC) has long-term responsibility for archiving GPM products. Additionally, GES DISC is helping to migrate 66 products to the cloud, including IMERG Early.[4] User statistics show that PPS and GES DISC show increasing downloads of GPM products.

Scott Braun [GSFC—*Atmosphere Observing System (AOS) Project Scientist*] gave an overview of the upcoming NASA **AOS mission** and how it will continue to advance our knowledge of precipitation science. The AOS mission is a response to the candidate measurement approaches outlined in the 2017 Earth Science Decadal Survey, including Aerosols, and Cloud, Convection, and Precipitation.[5] AOS objectives include acquiring data on climate feedback and convective storms, air pollution, and relationships between storm vertical motions and microphysics. Although the AOS architecture has not been finalized, the latest information can be found at the AOS mission link above.

Erich Stocker [GSFC—*GPM Deputy Project Scientist for Data* and *Precipitation Processing System Project Manager*] discussed the status of GPM data products. The NASA PPS started reprocessing of V07 GPM products in December 2021. However, IMERG is still at V06 in a hybrid format (see **GPM Data News** for more details and updates). He concluded by encouraging PMM data users to review updates from the GPM Data News page for awareness as PPS will continue to

[4] IMERG Early has only forward propagation (extrapolating forward in time), while IMERG Late has forward and backward propagation (allowing interpolation).

[5] The report is called **"Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space."** Aerosols and Cloud, Convection, and Precipitation are two of the five Designated Observables (DO) the decadal survey identified. These two DOs were combined in one mission concept that was later named the Atmosphere Observing System (AOS).

have stricter security requirements that may make it harder for end users to access and download data.

David Wolff [NASA's Wallops Flight Facility (WFF)—*GPM Deputy Project Scientist for Ground Validation* and *Ground Validation System Manager*] provided an overview of the **GPM Ground Validation (GV) program** and current activities. He described the ground validation site at NASA's Wallops Flight Facility (WFF), which includes several radars, *disdrometers* (which measure drop-size distribution), and a Precipitation Imaging Processor (PIP) package. He also noted that the GV program includes field campaigns e.g., IMPACTS, Marquette (a five-year mini-campaign conducted in collaboration with the National Oceanic and Atmospheric Administration's National Weather Service), and the **BiLateral Operational Storm-Scale Observation and Modeling** (BLOSSOM) project. He further noted that ground validation data processing software is now completely in Python format and available via GitHub. A system for integrating multi-platform data also is being developed. He concluded by stating that the GV program has state-of-the-art ground and remote sensing instruments to acquire precipitation and microphysics data to validate GPM retrievals.

Andrea Portier [GSFC—*GPM Senior Applications Lead*] and **Dorian Janney** [GSFC—*GPM Outreach Coordinator*] concluded the NASA Programmatic discussion with an overview of GPM Applications and Outreach activities and a strategy to support decision making by users, as outlined in **Figure 1**. The applications and outreach team continues its focus on increasing the use of GPM data and products across communities through user engagement and outreach activities including workshops, e.g., **Applying Earth Observations to Extreme Weather Events** held at the 2021 Fall Meeting of the American Geophysical Union (AGU), trainings (e.g., **2022 GPM Mentorship Program**), interviews, providing visualization tools, and developing GPM application case studies. A continuing and integral part of GPM outreach is the GPM website, which attracts thousands of visitors, serves increasing numbers of downloads each month, and provides resources for ST members who are giving their own outreach presentations. The public can also access a range of K-12 materials showcasing the use of GPM data to allow students to understand climate science, climate change, and the water cycle, among many other topics.

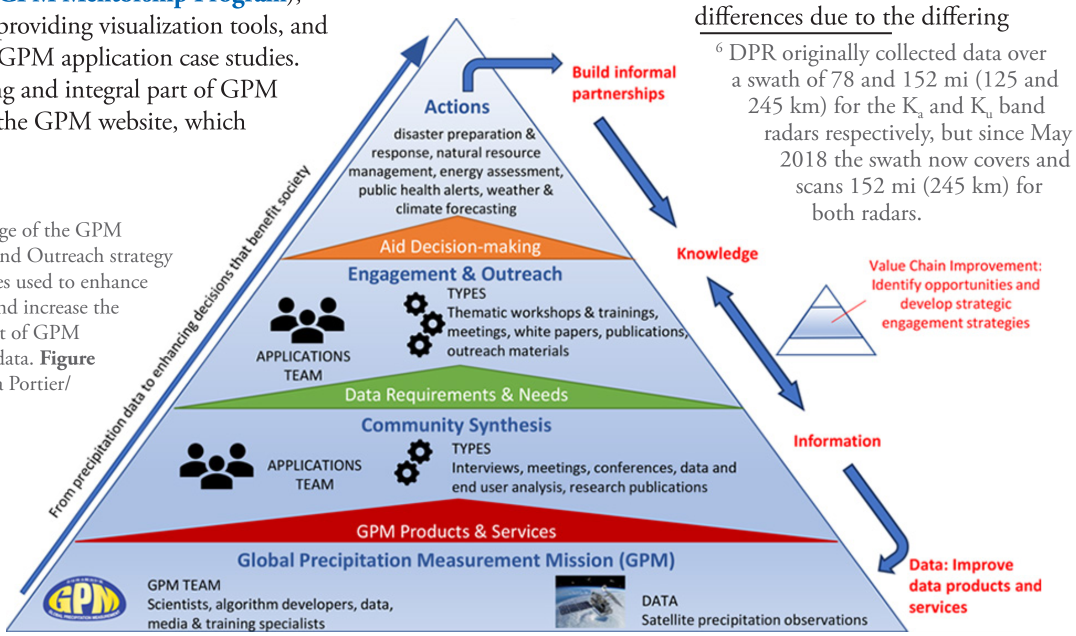

Figure 1. Image of the GPM Applications and Outreach strategy and approaches used to enhance applications and increase the societal benefit of GPM precipitation data. **Figure credit:** Andrea Portier/ GSFC/SSAI

JAXA

Takuji Kubota [JAXA Earth Observation Research Center (EORC)—*JAXA GPM Program Scientist*] presented updates on the JAXA PMM Program. He gave an overview of the role of JAXA in the GPM satellite and the PMM ST, summarizing the development of the GPM's radar instrument, the K_u/K_a-band Dual Frequency Precipitation Radar (DPR), the JAXA launch of the GPM CO , and the development of algorithms. Specifically, Kubota discussed that data from DPR V07 algorithm corresponds to the change in scan pattern that occurred in May 2018.[6] This change has led to more accurate estimates of precipitation rate and improvements in cloud physics that support the Japan Meteorological Agency's (JMA) weather models. He also highlighted the recent joint field campaign with JMA, which occurred from June to October 2022, and focused on heavy rain events in Japan. Future plans include development of the JAXA Nex-Gen precipitation radar, which will combine cloud profiling with Doppler capabilities.

Yukari Takayabu [University of Tokyo—*JAXA GPM Project Scientist*] presented several highlights from recent science results using GPM satellite data, many of which focused on the DPR and radar retrievals. She discussed the impact of missing shallow storms due to reflectivity profiles being affected by surface clutter (e.g., the *DPR blind zone*). The surface clutter revealed that there are monthly latitudinal and seasonal differences due to the differing

[6] DPR originally collected data over a swath of 78 and 152 mi (125 and 245 km) for the K_a and K_u band radars respectively, but since May 2018 the swath now covers and scans 152 mi (245 km) for both radars.

environmental conditions. Takayabu also reported on an examination of the updated GPM DPR ice precipitation categories, including flags for *graupel* (supercooled water droplets) and heavy ice precipitation. She noted that some caution is advised when using these new products as their processing is still in progress. Further, she summarized science studies that use the Global Satellite Mapping of Precipitation (GSMaP) multisatellite product,[7] which included the utilization of ground validation to assess regional-scale over and under estimations—for example,Takaybu noted that by leveraging networks over Vietnam and small islands in the Pacific, JAXA ST members are collaborating to create a real-time weather watch system.

Nobuhiro Takahashi [Nagoya University] gave a detailed overview of updates to the DPR algorithm, including highlighting the major updates to the DPR V07 product, noting that the Algorithm Theoretical Basis Document (ATBD) for DPR V07 is available from NASA and JAXA. Major changes to the new product version include a drop size distribution (DSD) parameter update and added consideration of soil moisture. He concluded that there have been some changes to variable names from V06 to V07, and strongly advised users to read the ATBD and metadata for more information.

Moeka Yamaji [JAXA Earth Observation Research Center (EORC)—*JAXA Applications Lead*] concluded the session by outlining several examples of JAXA Applications, including some pertaining to GSMaP and DPR. She noted that the Pacific Islands use the real-time GSMaP product to monitor offshore cyclones and tropical disturbances. Further, the 22-year GSMaP data record is being used to monitor extremes. The GSMaP data are also being used for educational outreach initiatives, including the Hobonichi Globe, an app-plus-artifact package that provides an augmented reality view of Earth and can display (for example) rainfall data. The package can be used on smartphones, tablets, and provides ample applications for education. Yamaji also outlined several applications of the DPR—for example, utilizing observations for weather forecasting and calibrating and monitoring ground radars in Australia.

GPM Algorithm Updates

This session provided information and updates on various aspects of the five major algorithms of GPM. Full documentation and detailed updates on each algorithm are available at the **Precipitation Data Directory**.

Dual Frequency Radar

The DPR team provided updates on DPR-related work, including developing a mirror-image technique to estimate path-integrated attenuation (PIA). PIA can be used to improve precipitation estimates. The DPR team noted that results are very preliminary, and more work is needed to assess the utility of this technique.

GPM Goddard Profiling Algorithm (GPROF) for GMI

This GPROF team's update covered several topics, including developing GPROF V07, describing methods to tackle orographic precipitation, introducing an AI version of GPROF for V08, and developments toward improving the *a priori* database to help constrain outputs from GPM constellation radiometers.

GPM Combined Radar–Radiometer Algorithm

The GPM Combined Radar–Radiometer Algorithm (CORRA) team highlighted changes and improvements to the CORRA V07 algorithm. They noted that CORRA V07 estimates over land are less biased relative to V06; however, the algorithm still shows low biases regionally over land. Estimates over ocean are fairly bias-neutral aside from high latitudes. An effort is under way to use radiometer data to recover precipitation missed by DPR. They concluded that V07 TRMM and GPM estimates by CORRA are consistent over ocean and land.

Convective-Stratiform Heating

The Convective-Stratiform Heating (CSH) team provided an overview on latent heating (LH) retrievals. They described the impacts that LH has towards atmospheric processes, including how LH via precipitation production is a principal source of atmospheric diabatic heating. Also noted was that the vertical distribution of LH release modulates large-scale meridional and zonal circulations within the tropics and modifies the energetic efficiencies of mid-latitude weather systems.

Integrated Multi-Satellite Retrievals for GPM

The IMERG team reported on IMERG product V06 and the status of V07, noting that the IMERG V06 Final product is available but only through September 2021, as the team prepares the transition between version 06 and 07. The team noted that IMERG V06 Early and Late product runs continue through to the present day, and that IMERG V07 is not yet available to the public, but its development is underway. The team also described the new processing scheme for V07 and IMERG variable name changes being implemented to reduce confusion about the use of specific precipitation variables.

[7] GSMaP is essentially the JAXA analog of IMERG.

Science Team Projects and Activities

This section includes updates about ST member projects, research, and associated activities. The session was divided into five thematically focused topics: Precipitation Algorithms, Precipitation Microphysics, Large-Scale Precipitation Processes, Weather, and Climate Modeling

Precipitation Algorithms

Presenters during this session covered a range of research topics related to the algorithms used with DPR and GMI. (The algorithms themselves are discussed in the previous section.) Several presentations reported on analysis of data from GMI and DPR that could improve estimates of shallow, cold-season precipitation. This is a regime that has been problematic to detect from GPM data owing to the poor contrast between precipitation and the surface. One presenter described a method to classify the snow precipitation into shallow and deep systems. To better discriminate the surface from the snow signal, the Snow retrievaL ALgorithm fOr gMi (SLALOM; which is the snow retrieval algorithm for GPM. This algorithm includes a surface classification step known as Passive microwave Empirical cold Surface Classification Algorithm (PESCA).

There was a presentation that included a description of a physical melting model that was used to produce a representation of frozen hydrometeors in CORRA. This provides a controlled thermodynamic framework from which to evolve melting ice, to compute their radar scattering parameters, and to develop methods to vary these parameters so as to properly simulate the DPR path attenuation.

Another presenter discussed a method to classify DPR-observed precipitation type in both their horizontal and vertical dimensions. This information is useful to multiyear GPM precipitation science investigations to evaluate GPM algorithms, and how precipitation type is represented in global and regional scale models.

The session ended with a survey of space-based precipitation estimation that is expected in the fast-developing multisatellite, multisensor era, which will likely include small or CubeSat-sized, high-quality—but short-duration—satellite observations.

Precipitation Microphysics

Presenters during this session described different approaches for classifying and estimating precipitation using GPM data products and ground-based observations. There were discussions of various methodologies using brightness temperatures (T_b) from both DPR and GMI observations to estimate the production of ice and snow particle shapes against ground-based observations.

One presenter described a specific method to classify hail with Tb and highlighted a Hail Climatology Visualization Portal using T_b—see **Figure 2**. There is a hypothetical disconnect between hailstones aloft in the cloud where the satellite instruments detect them and hailstones reaching the ground where humans experience them. To investigate the disconnect, researchers are developing a strategy around using aircraft-based observations, numerical models involving hail dynamics, and observations from ground radars.

Large-Scale Precipitation Processes

Several presenters in this session focused on storm system dynamics—ranging from synoptic to mesoscale precipitation events. PMM ST members reported on the data analysis for the GPM and TRMM constellation of

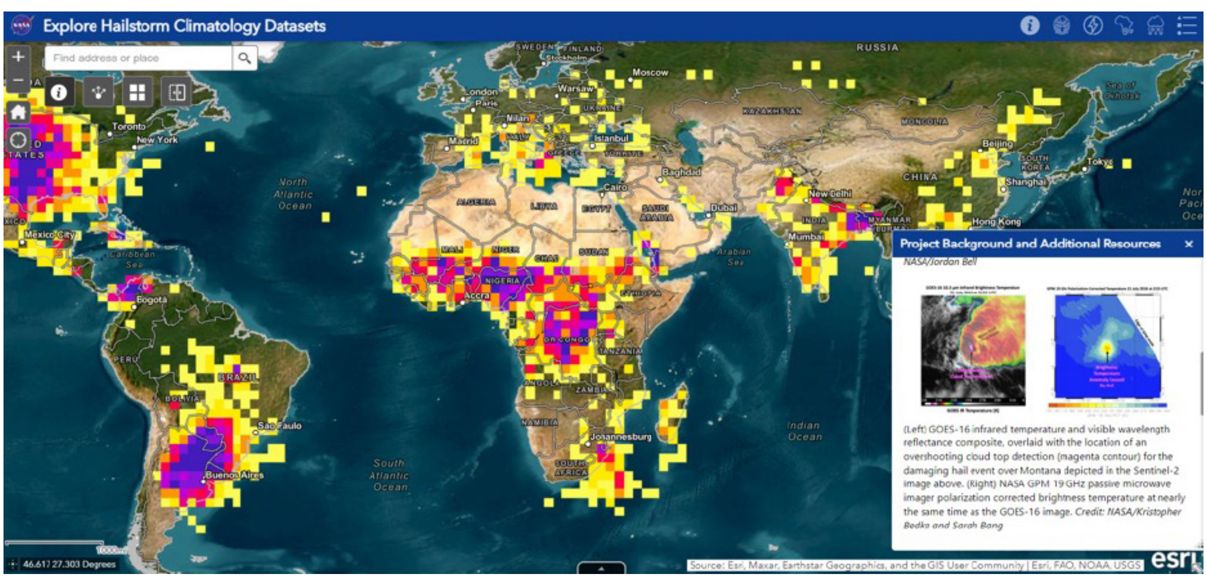

Figure 2. The NASA Hail Climatology Visualization Portal uses NASA GPM 19-GHz passive-microwave-imager, polarization-corrected, brightness temperature to help develop the hail climatology dataset. **Figure credit:** Sarah Bang/Marshall Space Flight Center

radiometers as well as the GPM and TRMM radars that could help identify the intensity and severity of tropical cyclones, atmospheric rivers, and thunderstorms.

Another presenter demonstrated the NASA/Jet Propulsion Laboratory (JPL) Tropical Cyclone Information System (TCIS), which includes a 12-year archive of multisatellite hurricane observations along with the ability to quantify cyclone characteristics based on its two-dimensional rainfall structure. The diagnostics from evaluating these large-scale precipitation events using GPM and TRMM data can be used to evaluate weather and climate models and benchmarks. Other presenters described other methods for evaluating mid- and high-latitude precipitation. Efforts included analyzing the GPM precipitation products used within IMERG over high-latitude oceans and over snow and ice surfaces. These analyses are challenging because of the sparseness and inaccuracy of in situ precipitation observations in these areas. The analysis will include use of the Merged CloudSat–TRMM–GPM (MCTG) precipitation product, and will produce bias correction values for GPM precipitation products.

The session ended with a presentation describing the use of IMERG to objectively define the onset and demise of rainy seasons in regions of the tropical belt (e.g., Florida, Northern Australia, South Asia, and Central America). Rainy season onset date is closely tied to rainy season length and total seasonal rainfall anomaly, making its monitoring useful for providing seasonal outlooks. Results suggest that IMERG rainfall has a potential to help understand terrestrial rainfall evolution in several regions and may lead to effective seasonal outlooks.

Weather and Climate Models

Several presenters in this session focused on approaches to evaluate bias and various degrees of cloud feedbacks within models. There were presentations that reported on the impact and representation of the Inter-Tropical Convergence Zone (ITCZ) within models as well as on extratropical cloud feedbacks—as both dynamics can have large uncertainties and therefore a large effect on model outcomes. Current methodologies and developments of simplified models using GPM data are underway to advance process understanding and improve model parameters.

Societal Applications

Presenters in this session focused on new research avenues using GPM data to improve decision making at local and regional scales. One presenter showcased a method to develop a GPM precipitation-based risk index for rainfall-based contamination in North Carolina by developing relationships between well-water contaminants, hydrology, and rainfall. Another ST member discussed the development of a climatology of conditional soil moisture over the globe using IMERG as input. Several other presenters reported on application projects using IMERG, including evaluating IMERG within a model to accurately predict streamflow dynamics in wet tropical ecosystems (e.g., the Amazon), characterizing extreme precipitation events to reduce uncertainties within landslide forecasts, and evaluating IMERG against rain gauge networks in Turkey to improve flood models. Lastly, a presenter discussed IMERG validation and level of performance against rain gauge data across South America. The information from this analysis will help produce a reliability map and develop new products based on user needs.

Conclusion

The 2022 PMM STM brought together scientists from around the world to engage on a range of topics that advance understanding of precipitation science, algorithms, and contributions to applications. The STM highlighted new projects and activities enabled by the PMM scientific community. During the meeting's final remarks, there was a request for team members to continue to share highlights and publications with the GPM management team as well as strong encouragement to continue or initiate collaborating with other colleagues.

The next PMM STM will likely be held in September 2023. Details will be posted on the GPM website once they become available.

Acknowledgements

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NASA-Funded Scientists Estimate Carbon Stored in African Dryland Trees

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EDITOR'S NOTE: This article is taken from *nasa.gov*. While this material contains essentially the same content as the original release, it has been rearranged and wordsmithed for the context of *The Earth Observer*.

Using commercial, high-resolution satellite images and artificial intelligence, an international team including NASA scientists mapped almost 10 billion individual trees in Africa's drylands to assess the amount of carbon stored outside of the continent's dense tropical forests. The result is the first comprehensive estimate of tree carbon density in the Saharan, Sahel, and Sudanian zones of Africa. The team reported its findings March 1 in **Nature,** and the data are free and publicly available.

The researchers found there are far more trees spread across semi-arid regions of Africa than previously thought—but that they also store less carbon than some models have predicted. In the new study, the team estimated roughly 0.84 petagrams of carbon are locked up in African drylands—a *petagram* is 1 billion metric tons—see **Figure 1**.

Having an accurate tree carbon estimate is essential for climate change projections, which are influenced by how long trees and other vegetation store carbon. This *carbon residence time*, as scientists call it, is very short for grasses and bushes, which grow seasonally, but much longer for trees that grow for years. Knowing how much carbon a landscape stores is dependent on knowing exactly what is growing there.

Beyond the vast tropical forests spread across the middle of the continent, African landscapes range from dry grasslands with a few trees to savannahs with scattered trees to more humid areas with many scattered trees. This dispersed tree cover has made it difficult for scientists working to estimate the number of trees in these areas, and there have often been over- or underestimates—see **Figure 2**. Yet such measurements are essential for conservation efforts and for understanding the **carbon cycle on our planet**.

"Our team gathered and analyzed carbon data down to the individual tree level across the vast semi-arid regions of Africa or elsewhere—something that had previously been done only on small, local scales," said lead project scientist **Compton Tucker** [NASA's Goddard Space Flight Center]. Previous satellite-based estimates of tree carbon in Africa's drylands often mistook grasses and shrubs for trees. "That led to over-predictions of the carbon there."

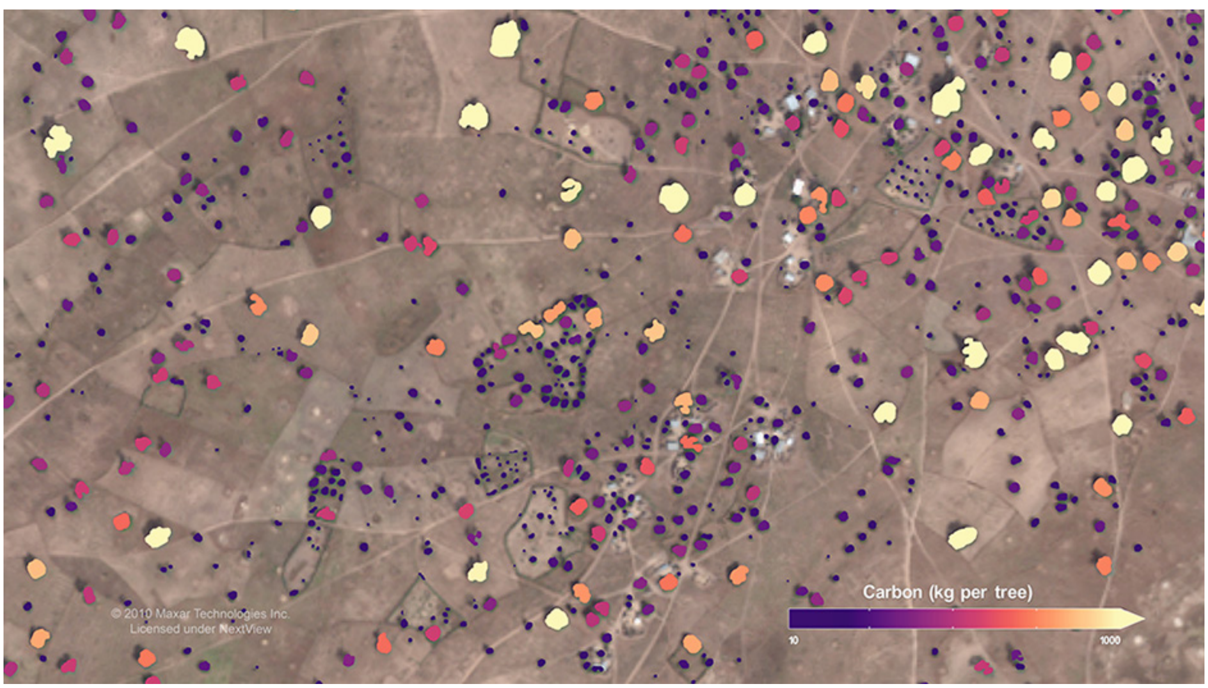

Figure 1. Individual trees identified in satellite imagery—color mapped by the amount of carbon they contain. Deep purple indicates lower carbon levels; yellow-white indicates higher levels. **Figure credit:** NASA's Scientific Visualization Studio

Figure 2. The animation shows how scientists mapped the sparse tree cover in semi-arid Africa to better calculate how much carbon is being stored. **Figure credit:** NASA's Scientific Visualization Studio

Carbon is constantly cycling between the land, the atmosphere, the ocean, and back. Trees remove carbon dioxide—a greenhouse gas—from Earth's atmosphere during the process of photosynthesis and store it in their roots, trunks, branches, and leaves. For this reason, increasing tree cover is often suggested as a way to offset ever-increasing carbon emissions.

In the new study, the team used sophisticated machine learning and artificial intelligence algorithms to sort through more than 326,000 commercial satellite images from the QuickBird-2, GeoEye-1, WorldView-2, and WorldView-3 satellites (operated by Maxar Technologies). The researchers acquired the images through **NASA's Center for Climate Simulation** and leveraged its Explore/ADAPT Science Cloud to organize and prepare the images for machine learning processing.

Photo 1. Scientists measured the circumference of trees and took other measurements to help relate tree crown area in the satellite images to how much carbon is stored. **Photo credit:** Martin Brandt/University of Copenhagen, Denmark

Martin Brandt [University of Copenhagen] compiled AI training data from 89,000 individual trees. Brandt's colleague **Ankit Kariyaa** [University of Copenhagen] adapted a neural network so that computers could detect the individual trees in high-resolution 50-cm (~20-in) scale images of Africa's drier, less verdant landscapes.

The researchers defined a tree as anything with a green, leafy crown and an adjacent shadow. From this, they trained the machine learning software to count the trees during millions of hours of supercomputing on the Blue Waters supercomputer at the University of Illinois. When the team compared their machine-learning results with human assessments of the landscape, the computers were 96.5% correct in measuring tree-crown area—see **Photos 1** and **2**.

From measurements of tree crown area, the scientists can derive the amount of carbon in each tree's leaves, roots, and wood using allometry—the study of how the characteristics of living creatures change with size. A group led by **Pierre Hiernaux** [University of Toulouse] examined 30 different species of trees to measure leaf mass, wood mass, and root mass. They assessed those masses of carbon and established a statistical relationship to tree crown area.

The **African tree carbon data** are publicly available with a **viewer app** developed by the team. The app allows people to view every tree in the study area and the amount of carbon it stores. These data could be useful for scientists and students studying the carbon cycle, policymakers trying to improve conservation efforts, and farmers who want to determine the carbon stored in their farm. ■

Photo 2. Field scientists measure the area of tree crowns and the associated masses of leaves, roots, and roots, of every tree in the allometry used to determine how much carbon is stored within different parts of the tree. The laborious work is necessary to convert tree crown area into carbon estimates of trees. **Photo credit:** Martin Brandt/University of Copenhagen, Denmark

NASA Space Mission Takes Stock of Carbon Dioxide Emissions by Countries

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EDITOR'S NOTE: This article is taken from *nasa.gov*. While this material contains essentially the same content as the original release, it has been rearranged and wordsmithed for the context of *The Earth Observer*.

A NASA Earth-observing satellite has helped researchers track carbon dioxide (CO_2) emissions for more than 100 countries around the world. The pilot project offers a powerful new look at the CO_2 being emitted in these countries and how much of it is removed from the atmosphere by forests and other carbon-absorbing sinks within their borders. The findings demonstrate how space-based tools can support insights on Earth as nations work to achieve climate goals.

The international study, conducted by more than 60 researchers, used measurements made by NASA's **Orbiting Carbon Observatory-2** (OCO–2) mission,[1] as well as a network of surface-based observations, to quantify increases and decreases in atmospheric CO2 concentrations for 2015–2020—see **Figure 1**. Using this measurement-based (or top-down) approach, the researchers were then able to infer the balance of how much CO_2 was emitted and removed.

Although the OCO–2 mission was not specifically designed to estimate emissions from individual nations, the findings from the 100-plus countries come at an opportune time. The first **Global Stocktake**—a process to assess the world's collective progress toward limiting global warming, as specified in the 2015 Paris Agreement—takes place in 2023.

"NASA is focused on delivering Earth science data that addresses real world climate challenges—like helping governments around the world measure the impact of their carbon mitigation efforts," said **Karen St. Germain** [NASA Headquarters—*Director of the Earth Science Division*]. "This is one example of how NASA is developing and enhancing efforts to measure carbon emissions in a way that meets user needs."

Traditional activity-based (or *bottom-up*) approaches to carbon measurement rely on tallying and estimating how much CO_2 is being emitted across all sectors

[1] Launched in 2014, the OCO-2 satellite maps natural and human-made **CO2 concentrations** with the help of three camera-like spectrometers. These devices are tuned to detect the unique spectra, or light signature, of CO2. They measure the gas indirectly by how much reflected sunlight it absorbs in a given column of air.

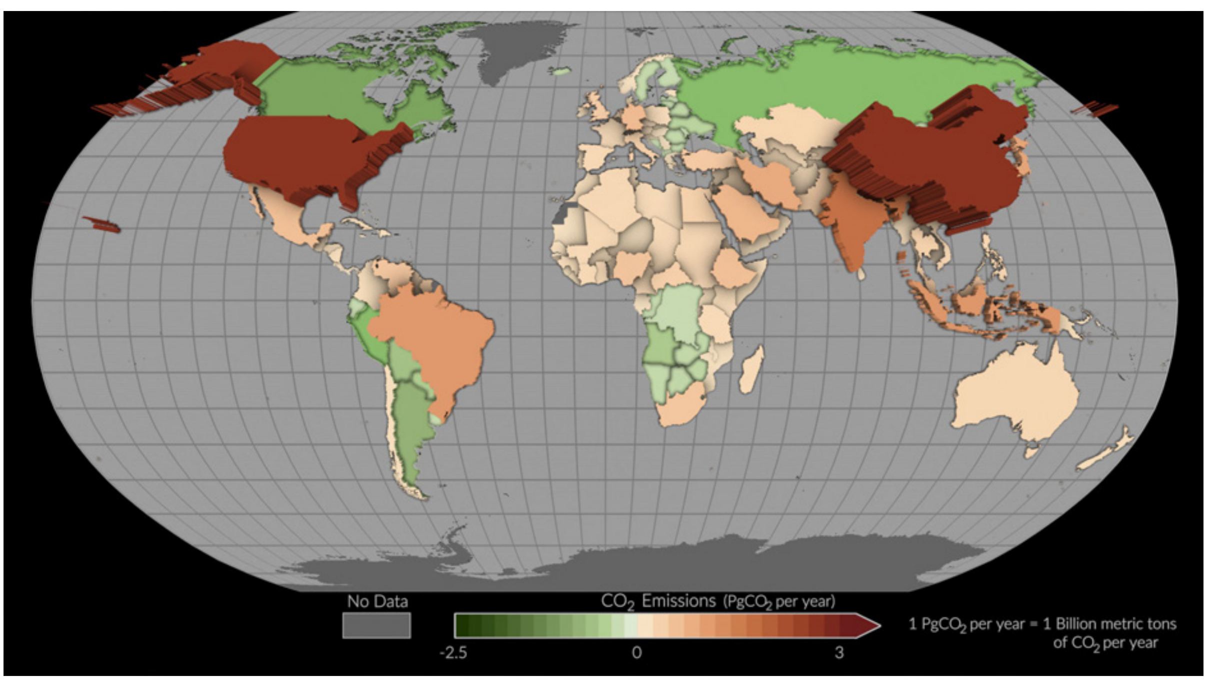

Figure 1. This map shows mean net emissions and removals of carbon dioxide (CO_2) for 2015–2020 using estimates informed by NASA's OCO–2 satellite measurements. Countries where more CO_2 was removed than emitted appear as green depressions, while countries with higher emissions are tan or red and appear to pop off the page. **Figure credit:** NASA's Scientific Visualization Studio

of an economy, such as transportation and agriculture. Bottom-up carbon inventories are critical for assessing progress toward emission-reduction efforts, but compiling them requires considerable resources, expertise, and knowledge of the extent of the relevant activities.

This is why developing a database of emissions and removals via a top-down approach could be especially helpful for nations that lack traditional resources for inventory development, the study authors assert. In fact, the scientists' findings include data for more than 50 countries that have not reported emissions for at least the past 10 years.

The study provides a new perspective by tracking both fossil fuel emissions and the total carbon *stock* changes in ecosystems, including trees, shrubs, and soils—see **Figure 2**. The data is particularly useful for tracking CO_2 fluctuations related to land cover change. Emissions from deforestation alone make up a disproportionate amount of total carbon output in the *Global South*, which encompasses regions of Latin America, Asia, Africa, and Oceania. In other parts of the world, the findings indicate some reductions in atmospheric carbon concentrations via improved land stewardship and reforestation.

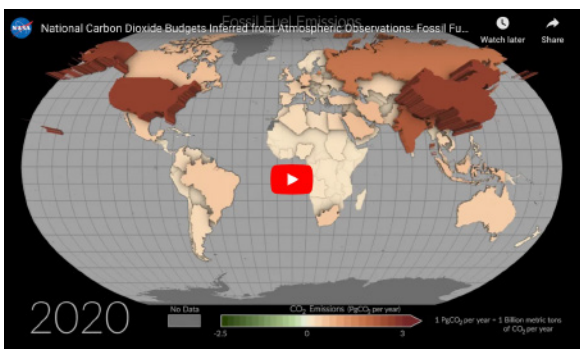

Figure 2. This animation shows yearly fossil fuel emissions by more than 100 countries for 2015–2020. Countries with high emissions, including the U.S. and China (seen here in dark red), appear to pop from the page, compared to those with lower emissions. **Figure credit:** NASA's Scientific Visualization Studio

The authors said that bottom-up methods for estimating CO_2 emissions and removals from ecosystems are essential. However, those methods are vulnerable to uncertainty when data are lacking or the net effects of specific activities, such as logging, aren't fully known.

"Our top-down estimates provide an independent estimate of these emissions and removals, so although they cannot replace the detailed process understanding of traditional bottom-up methods, we can check both approaches for consistency," said study author **Philippe Ciais** [Laboratoire des Sciences du Climat et de l'Environnement, *France*].

The study offers a complex picture of carbon moving through Earth's land, ocean, and atmosphere. In addition to direct human impacts accounted for by national inventories, unmanaged ecosystems like some tropical and boreal forests—where humans have a minimal footprint—can sequester carbon from the atmosphere, thus reducing potential global warming.

"National inventories are intended to track how management policies impact emissions and removals of CO_2," said study author **Noel Cressie** [University of Wollongong, *Australia*]. "However, the atmosphere doesn't care whether CO_2 is being emitted from deforestation in the Amazon or wildfires in the Canadian Arctic. Both processes will increase the concentration of atmospheric CO_2 and drive climate change. Therefore, it is critical to monitor the carbon balance of unmanaged ecosystems and identify any changes in carbon uptake."

Looking forward, the researchers said their pilot project can be further refined to understand how emissions from individual nations are changing—see **Figure 3**.

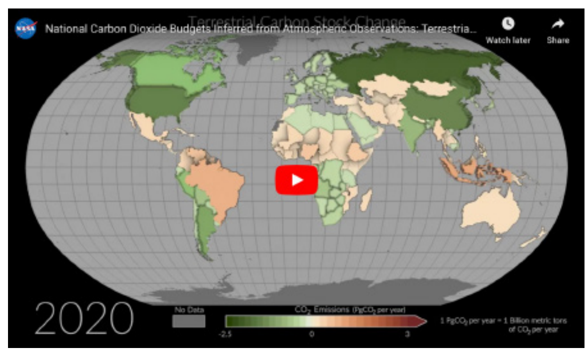

Figure 3. This animation illustrates changes in the amount of carbon stored in organic matter on land—called terrestrial carbon stock changes—for 2015–2020. Activities such as improved land stewardship and deforestation, which is more extensive in the tropics than other regions, affect these stock changes. **Figure credit:** NASA's Scientific Visualization Studio

"Sustained, high-quality observations are critical for these top-down estimates," said lead author **Brendan Byrne** [NASA/Jet Propulsion Laboratory]. "Continued observations from OCO-2 and surface sites will allow us to track how these emissions and removals change as the Paris Agreement is implemented. Future international missions that provide expanded mapping of CO_2 concentrations across the globe will allow us to refine these top-down estimates and give more precise estimates of countries' emissions and removals." ■

NASA Uses 30-Year Satellite Record to Track and Project Rising Seas

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EDITOR'S NOTE: This article is taken from *nasa.gov*. While this material contains essentially the same content as the original release, it has been rearranged and wordsmithed for the context of *The Earth Observer*.

The average global sea level rose by 0.11 in (0.27 cm) from 2021 to 2022, according to a NASA analysis of satellite data. That's the equivalent of adding water from a million Olympic-size swimming pools to the ocean every day for a year and is part of a multidecade trend of rising seas.

Since satellites began observing sea surface height in 1993 with the U.S.–French **TOPEX/Poseidon** mission, the average global sea level has increased by 3.6 in (9.1 cm), according to NASA's Sea Level Change science team. The annual rate of rise—or how quickly sea level rise is happening—that researchers expect to see also increased from 0.08 in (0.20 cm) per year in 1993 to 0.17 in (0.44 cm) per year in 2022. Based on the long-term satellite measurements, the **projected rate of sea level rise** will hit 0.26 in (0.66 cm) per year by 2050—see **Figure**.

"We have this clear view of recent sea level rise—and can better project how much and how quickly the oceans will continue to rise—because NASA and Centre National d'Études Spatiales (CNES) [French Space Agency] have gathered decades of ocean observations. By combining that data with measurements from the rest of the NASA fleet, we can also understand why the ocean is rising," said **Karen St. Germain** [NASA Headquarters (HQ)—*Director of the Earth Science Division*]. "These fundamental climate observations help shape the operational services of many other federal and international agencies who are working with coastal communities to mitigate and respond to rising waters."

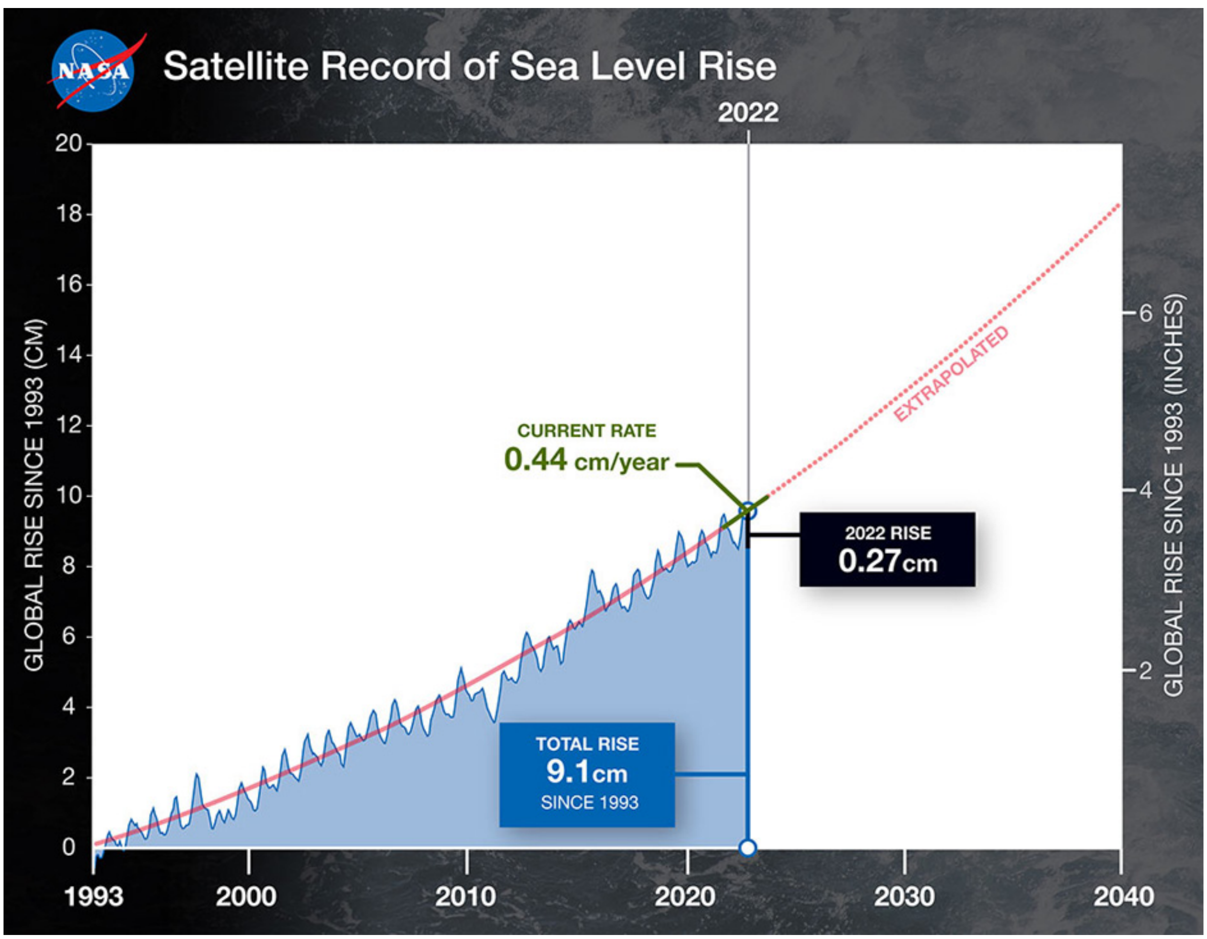

Figure. This graphic shows rising sea levels (in blue) from data recorded by a series of five satellites starting in 1993. The solid red line shows the trajectory of rise for 1993–2022, illustrating that the rate of rise has more than doubled. If this trend continues, by 2040, sea levels could be 3.66 in (9.3 cm) higher than today. **Figure credit:** NASA/JPL

The 2022 increase was less than the expected annual rate because of a **mild La Niña**. During years with an especially strong La Niña climate pattern, average global sea level can even temporarily drop because weather patterns shift in a way that leads to more rainfall over land instead of the ocean.

"With an increasing demand for accurate and timely climate information, NASA is committed to providing annual sea level observations and future projections in order to help vulnerable communities around the world better understand the risks they face in a new climate," said **Nadya Vinogradova Shiffer** [HQ—*Physical Oceanography Program Scientist and Manager*]. "Timely updates are key to showing which climate trajectory we are on."

Despite natural influences like La Niña, sea levels continue to rise because of human-caused climate change driven by the excess amounts of greenhouse gases like carbon dioxide that society pumps into the atmosphere. Climate change is melting Earth's ice sheets and glaciers, adding more fresh water to the ocean, while warming causes the expansion of seawater. Both of these effects contribute to rising seas, overriding many natural effects on sea surface height.

"Tracking the greenhouse gases that we add to the atmosphere tells us how hard we're pushing the climate, but sea levels show us how much it's responding," said **Josh Willis** [NASA/Jet Propulsion Laboratory (JPL)—*Oceanographer*]. "These measurements are a critical yardstick for how much humans are reshaping the climate."

The measurements of sea surface height that began 30 years ago with TOPEX/Poseidon have continued through four subsequent missions led by NASA and partners, including the French space agency CNES, European Space Agency (ESA), and the U.S. National Oceanic and Atmospheric Administration (NOAA). The most recent mission in the series, **Sentinel-6/Jason–Continuity of Service** (CS), consists of two satellites that will extend these measurements through 2030. The first of these two satellites, **Sentinel-6 Michael Freilich**,[1] launched in 2020, with the second slated to head to orbit in 2025.

"The 30-year satellite record allows us to see through the shorter-term shifts that happen naturally in the ocean and helps us identify the trends that tell us where sea level is headed," said **Ben Hamlington** [JPL], who leads NASA's Sea Level Change science team.

Scientific and technical innovations by NASA and other space agencies have given researchers a better understanding of the current state of the ocean on a global scale. Specifically, **radar altimeters** have helped produce ever-more precise measurements of sea level around the world. To calculate sea level height, they bounce microwave signals off the ocean's surface and record the time the signal takes to travel from a satellite to Earth and back, as well as the strength of the return signal.

When altimetry data from all ocean basins is combined with more than a century of observations from coastal surface-based sources, together they dramatically expand and improve our understanding of how sea surface height is changing on a global scale. And when those measurements of sea level are combined with other NASA data sets on ice mass, land motion, and other Earth changes, scientists can decipher why and how seas are rising. ■

[1] To learn more about **Michael Freilich** [NASA HQ—former *Director of the Earth Science Division*], for whom the Sentinel–6 Michael Freilich mission is named, see "**The Editor's Corner**" of the January–February 2020 issue of T*he Earth Observer* [**Volume 32**, **Issue 1**, p. 1].

NASA Earth Science in the News

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EDITOR'S NOTE: Presented in this column are summaries of articles that have been published on *nasa.gov* that have subsequently been reported on by other media outlets.

A Warmer World Causes Extreme Drought and Rain: 'Indisputable' New Research Proves It, March 13, 2023, ***washingtonpost.com***. Intense drought and heavy rainfall events occurred more often in the last eight years—the hottest years on record—than in the previous decade, according to a new study released in **Nature Water**. Warmer global temperatures are increasing the extent, duration, and severity of these extremes, the authors found, and are having more of an effect than natural climate patterns. "As the world warms, we're having more intense and more frequent wet and dry events around the world, which gives us a little insight into what's going to happen in the future," said **Matthew Rodell** [NASA's Goddard Space Flight Center (GSFC)], co-author of the study. Rodell said researchers have expected to see more droughts and floods in a warmer world based on climate model predictions, but "it's been really hard to prove." This new analysis, which uses direct NASA satellite observations, provides "indisputable" evidence that warmer global temperatures are increasing such extreme events, Rodell said. The team analyzed 1,056 extreme events from 2002 to 2021 using observations from NASA's Gravity Recovery and Climate Experiment (**GRACE**) and GRACE Follow-On (GRACE-FO) satellites—see **Figure 1**.

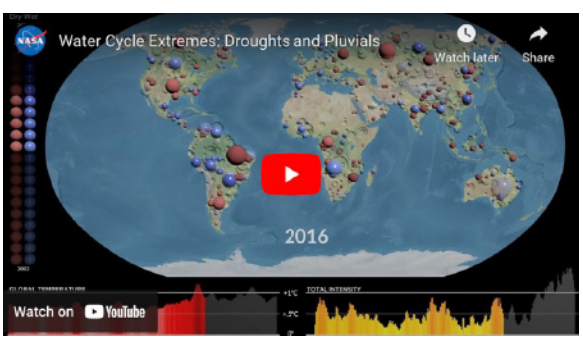

Figure 1. This visualization shows extremes of the water cycle over a twenty-year period (2002–2021) based on observations from the GRACE and GRACE-FO satellites. **Credit:** NASA Scientific Visualization Studio

NASA Teams with U.S. Forest Service to Tally America's Oldest Trees, April 21, 2023, ***phys.org***. America's forests help absorb more than 10% of our annual greenhouse gas emissions. While younger vegetation accumulates carbon more rapidly, old-growth forests contain more biomass overall and store more carbon. Substantial portions of U.S. old-growth forests have been lost in recent centuries. Surviving forests face a new generation of threats, including climate change-fueled wildfires, heavy rainfall events, and chronic temperature and drought stress. In an effort to provide stewardship for these resources the Department of Agriculture and Bureau of Land Management produced a first-ever national inventory of mature and old-growth forests on federal lands. Complementing the U.S. Forest Service's (USFS) boots-on-the-ground research, NASA-funded scientists are using a space-based instrument called **Global Ecosystem Dynamics Investigation (GEDI)** to provide a more detailed picture of the forests. "The partnership with NASA will help us do analyses we have not been able to do in the past," said **Jamie Barbour** [USFS]—see **Figure 2**.

Figure 2. From the International Space Station, GEDI's laser imager (lidar) can peer through dense canopies to observe nearly all of Earth's temperate and tropical forests. By recording how laser pulses are reflected by the ground and plant material at different heights, GEDI makes detailed measurements of the 3D structure of the planet's forests and fields. **Credit:** NASA Scientific Visualization Studio

"Living and fossil trees allow us to reconstruct temperature and precipitation history across hundreds or thousands of years, helping us better understand drought and wet periods." Marin Palmer [USFS] added, "We sometimes imagine these forests have never been touched by humans, but we have to look further back in history and understand that indigenous people were intentionally managing their forests for millennia. When we think about the threat climate change poses, it becomes a larger conversation about the need to be active stewards in our landscapes and ecosystems." ■

Mysterious Green Lasers Caught on Camera Belong to NASA Satellite, April 22, 2023, ***space.com***. Curator Daichi Fujii [Hiratsuka City Museum—Japan], set up motion-detecting cameras outside the museum to capture meteors and calculate their position, brightness, and orbit. What Fujii found was anything but what was expected. At first, the bright green lines that appeared on the camera footage were a mystery. However, further inspection revealed the beams were synchronized with a tiny green dot that was briefly visible between the clouds. It turns out the lasers were from one of NASA's Earth-orbiting satellites. The **Ice, Cloud and Land Elevation Satellite 2 (ICESat-2)** flew over the museum at the perfect time for its green lasers to be caught in action, beaming from orbit to Earth—see **Figure 3**. The museum's motion detector footage is the first time the satellite's laser beams have been caught on camera, according to a NASA **statement**.

Figure 3. On September 16, 2022, motion-sensing cameras set up to capture meteors instead photographed the laser beams of NASA's ICESat-2 satellite as it passed over Japan. **Credit:** Daichi Fujii, Hiratsuka City Museum/NASA

"ICESat-2 appeared to be almost directly overhead of [the museum], with the beam hitting the low clouds at an angle," wrote Tony Martino [NASA's Goddard Space Flight Center]. "To see the laser, you have to be in the exact right place, at the right time, and you have to have the right conditions." Located hundreds of miles up in space, the lasers have roughly the strength of a camera flash more than 100 yards away, and the laser's light has to reflect off something to be seen. However, on September 16, 2022, there were just enough clouds to scatter—but not obscure—the laser light, making it visible to the museum's cameras.

Navigating the Storm: Atmospheric Rivers Now Ranked Like Hurricanes, April 30, 2023, ***scitech-daily.com***. A NASA-funded study in the **Journal of Geophysical Research: Atmospheres** has shown that atmospheric rivers—bands of water vapor intensified by climate change—can be ranked on a new intensity scale, similar to hurricanes. The research mapped global patterns of these events over 40 years, identifying hotspots for the most intense atmospheric rivers. The findings will aid meteorologists and city planners in predicting and preparing for these potentially damaging weather events. The intensity scale ranks atmospheric rivers from AR-1 to AR-5 (with AR-5 being the most intense) based on how long they last and how much moisture they transport—see **Figure 4**.

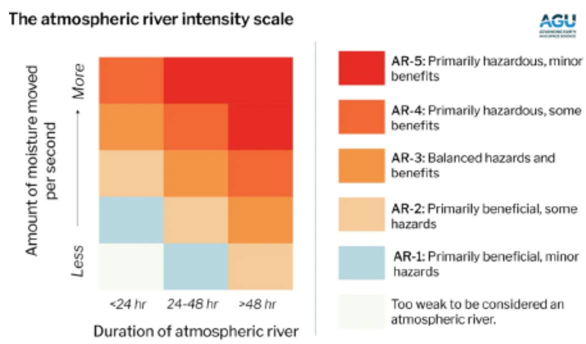

Figure 4. The intensity of an atmospheric river depends on how long it lasts (typically 24 to 72 hours; *horizontal axis*) and how much moisture it moves over one meter each second (measured in kilograms per meter per second; *vertical axis*). While weaker atmospheric rivers can deliver much-needed rain, more intense storms are more damaging and dangerous than helpful. **Credit:** AGU, after **Ralph, et al. (2019)**

The string of atmospheric rivers that hit California in December 2022 and January 2023 at times reached AR-4—see **Figure 5**. Earlier in 2022 the atmospheric river that contributed to disastrous flooding in Pakistan was an AR-5, the most damaging, most intense atmospheric river rating.

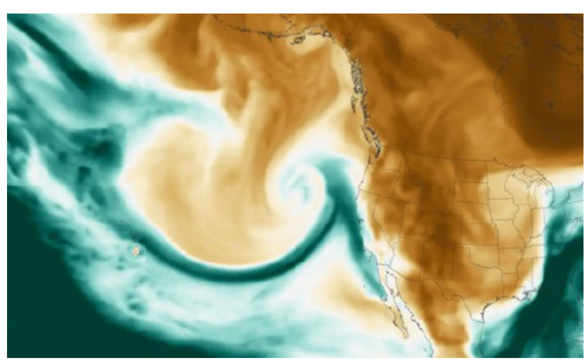

Figure 5. An atmospheric river drenched California in January 2023. This image was created using GEOS-5 data from the Global Modeling and Assimilation Office (GMAO) at NASA's Goddard Space Flight Center, and VIIRS data from NASA EOSDIS LANCE, GIBS/Worldview, and the Joint Polar Satellite System (JPSS). **Credit:** Lauren Dauphin/NASA Earth Observatory

The scale helps communities know whether an atmospheric river will bring benefit or cause chaos: The storms can deliver much-needed rain or snow, but if they're too intense, they can cause flooding, landslides, and power outages, as California and Pakistan experienced. "Atmospheric rivers are the hurricanes of the West Coast when it comes to the public's situational awareness," said **F. Martin Ralph** [Scripps Institution of Oceanography, University of California San Diego], co-author on the new study. "People need to know when they're coming, have a sense for how extreme the storm will be, and know how to prepare," he said. "This scale is designed to help answer all those questions."

NASA Data Helps Track Veterans' Exposure to Air Pollution, April 25, 2023, ***enn.com***. Researchers with the U.S. Department of Veterans Affairs (VA) are using NASA Earth observations of smoke and other air pollution to study the health impacts on veterans who were deployed to Afghanistan, Iraq, and other areas of Southwest Asia in the years after September 11, 2001. Military personnel who were deployed in these regions are at risk for developing respiratory problems due to exposures to particulate matter, smoke, and fumes from burn pits, dust storms, and other sources. Working with the VA, NASA-funded researchers created an online resource that compiles NASA satellite data on air pollution around specific military bases—see **Figure 6**. **Eric Garshick** [VA Boston] said the resource will be used to conduct research to assess associations between medical conditions and exposures encountered during deployment and ultimately help medical researchers identify affected veterans. Read more about the **project**, which was funded by **NASA's Earth Applied Sciences Health and Air Quality program area**.

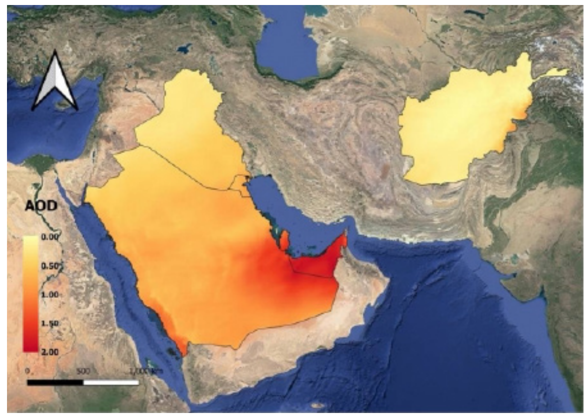

Figure 6. The project team created this map of the study region showing satellite-observed aerosol optical depth on July 24, 2006, as an example of the exposure estimation capabilities they have created for the VA. **Credit:** NASA/Meredith Franklin

Earth Science Meeting and Workshop Calendar

NASA Community

September 18–22, 2023
PMM Science Team Meeting
Minneapolis, MN
Invitation only

October 16–18, 2023
DSCOVR Science Team Meeting
NASA/GSFC, Greenbelt, MD

October 17–19, 2023
CERES Science Team Meeting
NASA/GISS, New York, NY
Meeting details forthcoming

Global Science Community

July 13–17, 2023
International Union of Geodesy and Geophysics (IUGG)
Berlin, Germany

July 16–21, 2023
International Geoscience and Remote Sensing Symposium (IGARSS)
Pasadena, CA

July 30–August 4, 2023
Asia Oceania Geosciences Society (AOGS)
Singapore

August 6–11, 2023
Ecological Society of America (ESA)
Portland, OR

August 13–17, 2023
American Chemical Society (ACS)
San Francisco, CA

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