Over Thirty Years Reporting on NASA's Earth Science Program

The Earth Observer

National Aeronautics and Space Administration

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The Editor's Corner

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EOS Senior Project Scientist

The Earth Observer continues to work on its transition to our **new website**. Implementing a completely new set-up is not without challenges and has taken a bit longer than anticipated. The plan is to have the site fully operational soon – current estimate is no earlier than (NET) June 2024. In the meantime, to reduce a gap between our continuous 35-year run of PDF issues and the rollout of the new website, the newsletter team decided to release one final PDF issue. To learn more about the status of *The Earth Observer*'s transition to online publication, see the *Update from the Executive Editor* on page 33 of this issue.

The launch of the new website for *The Earth Observer* is far from the only Earth Science launch we have to discuss. In our last issue we announced that the **Plankton, Aerosol, Cloud, ocean Ecosystem** (PACE) mission had successfully launched from Kennedy Space Center in the early morning of February 8, 2024. Just 63 days later, data from NASA's newest Earth-observing satellite **became available to the public** – see **Figure**. These data will extend and improve upon NASA's 20+ years of global satellite observation of our living oceans, atmospheric aerosols, and clouds, and initiate an advanced set of climate-relevant data records. Ultimately, PACE is the first mission to provide measurements that will enable prediction of the "boom–bust" cycle of fisheries, the appearance of harmful algae, and other factors that

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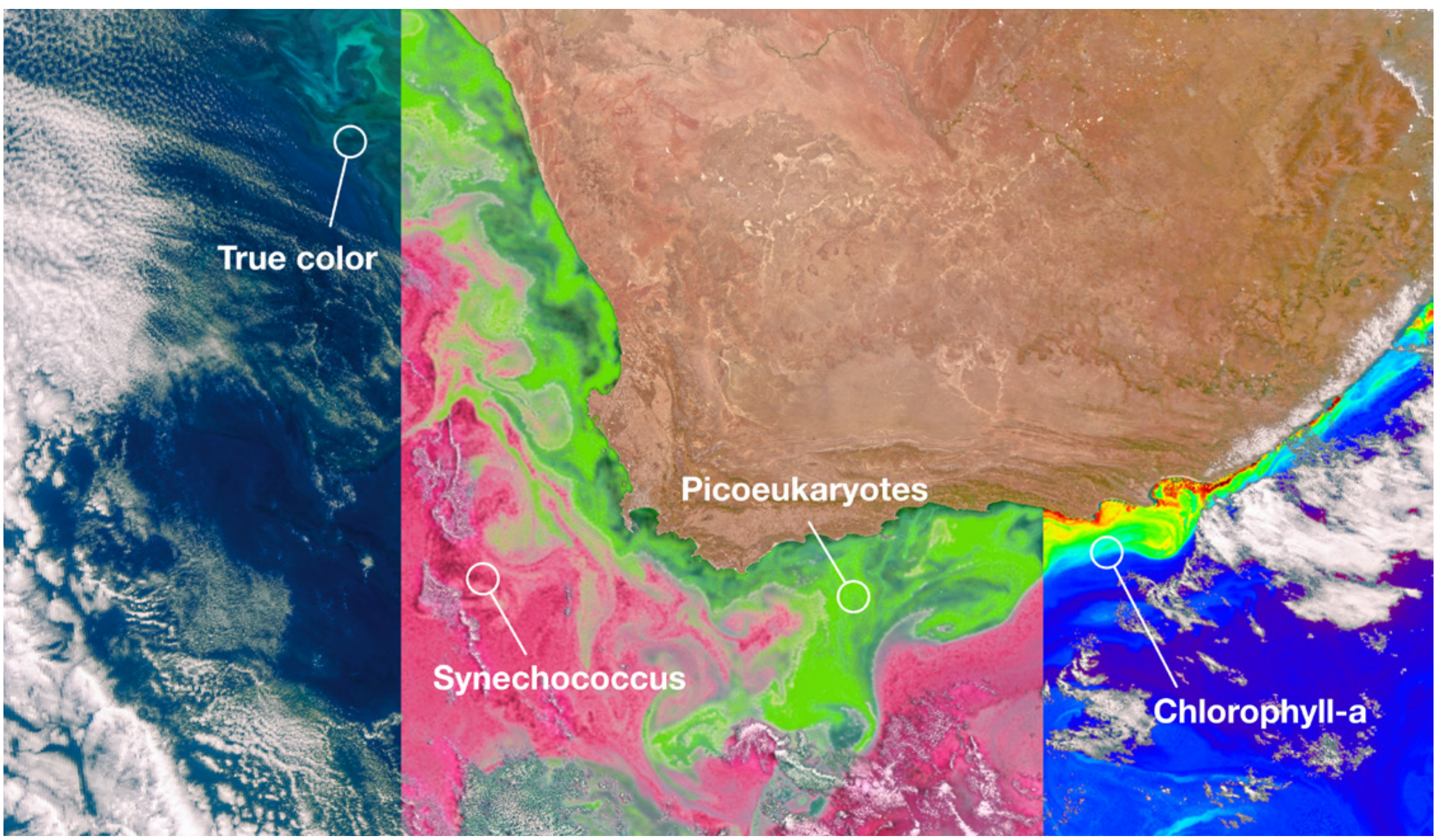

Figure. The Ocean Color Instrument (OCI) on NASA's PACE mission detects light across a hyperspectral range, which gives scientists new information to differentiate communities of phytoplankton – a unique ability of NASA's newest Earth-observing satellite. This first image released from OCI identifies two different communities of these microscopic marine organisms in the ocean off the coast of South Africa on February 28, 2024. The central panel of this image shows *Synechococcus* in pink and picoeukaryotes in green. The left panel of this image shows a natural color view of the ocean, and the right panel displays the concentration of chlorophyll-a, a photosynthetic pigment used to identify the presence of phytoplankton. **Image credit:** NASA

In This Issue

affect commercial and recreational industries. PACE also observes aerosols that influence air quality as well as the absorption and reflection of sunlight by both aerosols and clouds, which in turn impacts the radiation budget.

Along with the first image release, PACE produced a gallery of **first light imagery** to commemorate this initial data release and celebrate and highlight the advanced capabilities of PACE. Using the Ocean Color Instrument (OCI) aboard PACE, **Joseph Knuble** [NASA's Goddard Space Flight Center (GSFC)—*OCI Lead Instrument Systems Engineer*] created a series of images using only 3 of 288 hyperspectral wavelengths (e.g., visible Red–Green–Blue) provided by the state-of-the-art sensor. Congratulations to the entire PACE team on the mission's progress and these first light images.

In addition to PACE, the launch of NASA's **Polar Radiant Energy in the Far-InfraRed Experiment** (PREFIRE) is imminent. Selected through NASA's **Earth Venture program**,[1] PREFIRE will make the first full spectral measurements of Far InfraRed (FIR) radiation, revealing the full spectrum of Arctic radiant energy. Filling in this missing data from Earth's polar regions will help us understand how much of Earth's heat is lost to space. Analysis of PREFIRE's measurements will inform climate and ice models, providing better projections of how a warming world will affect sea ice loss, ice sheet melt, and sea level rise. The mission is designed for a pair of two 6U CubeSats to measure this little-studied portion of emitted radiant energy for clues about a warming Arctic – the region that behaves like our planet's thermostat, as it regulates the climate by venting excess energy received in the tropics.

The first PREFIRE CubeSat launch is scheduled NET May 22, 2024, aboard an Electron rocket to be launched from Rocket Lab's Launch Complex 1 in Māhia, New Zealand, with the launch of the other PREFIRE CubeSat to take place within three weeks of the first via the same rocket launched from the same location. These two small spacecrafts will will occupy two different 525 km altitude (326 mi), near polar, sun synchronous (97.5 deg inclination) orbits. Each CubeSat is equipped with a heritage miniaturized infrared spectrometer, covering the 3–54 μm wavelength region at approximately 0.84 μm spectral sampling, operating for about one seasonal cycle (about a year) with diurnal subsampling.

PREFIRE's Thermal IR Spectrometer (TIRS) instrument is equipped with flight-proven hardware and design, originating from both the **Mars Climate Sounder** (MCS) aboard the **Mars Reconnaissance Orbiter** (MRO), which was designed to map the three-dimensional structure of temperature, dust, water ice, and water vapor in the atmosphere of Mars, as well as **Diviner**, an instrument flying aboard NASA's Lunar Reconnaissance Orbiter (LRO), designed to measure surface temperatures on the Moon. PREFIRE has been jointly developed by NASA and the University of Wisconsin-Madison, with team members from the universities of Michigan and Colorado.

NASA recently announced the selection of six new Earth Venture Suborbital (EVS) missions that will deploy at various times from 2026 to 2029. These missions were from the EVS-4 Announcement of Opportunity. They are all aircraft investigations that include domestic and international studies of

[1] Earth Venture (EV) missions and solicitations are subdivided into four classifications: Missions (EVM), Instruments (EVI), Suborbital (EVS), and Continuity (EVC). PREFIRE, for example, was one of two winning proposals selected from the EVI-4 Announcement of Opportunity issued through the Research Opportunities in Earth and Space Science (ROSES). The other EVI-4 selection was the Earth Surface Mineral Dust Source Investigation (EMIT) mission, which launched to the International Space Station in July 2022.

fire-induced clouds, Arctic coastal change, air quality, landslide hazards, shrinking glaciers, and emissions from agricultural lands. NASA's suite of airborne missions complement what scientists can see from orbit, measure from the ground, and simulate in computer models.

Three lead investigators were chosen for each mission, with at least one required to be an early career scientist. Full staffing of the science teams and selection of complementary instruments will be competed in the coming months. A **recent NASA press release** provides more details on each EVS-4 mission and names the Principal Investigators. Congratulations to all the teams – especially the early career investigators – who will provide leadership for these suborbital investigations.

Turning to an update on a current Earth science mission, NASA's GRACE Follow-On (G-FO) mission continues to perform well.[2] The primary mission objective for G-FO is to provide continuity for the monthly GRACE mass-change observations [2002–2017] via its Microwave Interferometer (MWI) intersatellite range-change observations. The twin G-FO satellites (launched in May 2018) have been tracking Earth's water movements and global surface mass changes that arise from climatic, anthropogenic, and tectonic changes. As of April 2024, the G-FO project team has processed and released 65 monthly mass change and gravity fields – the most recent being for February 2024 (at the time of writing). G-FO also enables new insights into variations of ice sheet and glacier mass, land water storage, as well as changes in sea level and ocean currents.

G-FO was among the missions that went through the **2023 NASA Earth Science Senior Review**. The G-FO proposal submitted for the Senior Review advocated extending mission operations until 2026 and received an *Excellent* score. However, in light of overall budget constraints at NASA, the G-FO project's budget will be reduced (compared to the previous baseline) by 15% in fiscal year (FY) 2024, and 24% in FY 2025 and 2026. Despite these reductions, the G-FO team remains confident in its ability to continue delivering high-value and high-impact science data products by prioritizing science operations management and data latency over data reprocessing campaigns.

In terms of a "follow-on" to G-FO, the **2017 NASA Earth Science Decadal Survey Report** highlighted mass-transport monitoring through gravity change, or *Mass Change*, as one of five *designated observables* (i.e., top priorities for study) in Earth observations for the next decade in collaboration with international partners. Since then, NASA, the German Aerospace Center (DLR), and other partners have been working on Mass Change mission concepts. In late 2023, NASA and DLR signed an agreement to continue their more than two decades of collaboration on a Mass Change mission that will be known as GRACE–Continuity, or GRACE-C. Like its predecessors, GRACE-C will be a single satellite pair, but this time the precise gravity measurements will be obtained using a fully redundant Laser Ranging Interferometer (technology that was demonstrated on G-FO) in a polar orbit at 500 km (~311 mi) altitude. Critically, to avoid a data gap after G-FO, a launch date of no later than 2028 is targeted for GRACE-C.

To learn more about the latest activities of the G-FO Science Team – including a discussion of next generation gravity missions such as GRACE-C – turn to page 19 of this issue.

It is bittersweet to report the end of the CloudSat mission after nearly two decades of providing never-before-seen details of cloud vertical structure. As can be said of many NASA Earth science missions, CloudSat was an overachiever. Originally proposed as a 22-month mission, the spacecraft was recently decommissioned in March 2024 after almost 18 years of observations. The spacecraft, having reached the end of its lifespan and no longer able to make regular observations, was lowered into a *graveyard orbit* that will result in its eventual disintegration in the atmosphere. When launched in 2006, the mission's Cloud Profiling Radar (CPR) was the first 94 GHz wavelength (W-band) radar to fly in space. A thousand times more sensitive than typical ground-based weather radars, data from CPR has informed thousands of research publications and continues to help scientists make key discoveries, including the amount of ice and liquid water contained within clouds globally and the radiative implications of these amounts. Congratulations to the entire CloudSat team, past and present, especially PI **Graeme Stephens** and Project Manager **Deb Vane** [both at NASA/Jet Propulsion Laboratory]. To learn more, see the **news release about the end of CloudSat** that was released on April 23.

Closer to the ground, **NASA's Earth Science Technology Office** (ESTO), which manages the development of technologically advanced, reliable, and cost-effective components, instruments, and information systems that help NASA meet its science objectives, has reached a milestone: 25 years of managing the development of more than 1,100 new technologies for future science measurements. This diverse, forward-looking portfolio has nurtured new Earth-observing capabilities, informed **Decadal Surveys** and strategic planning, and generated numerous infusions and spinoffs. At least 269 ESTO technologies have been infused into Earth science missions, science campaigns, or other

[2] G-FO is a U.S.–German collaboration between NASA and the Helmholtz Centre Potsdam GeoForschungsZentrum (GFZ) [German Research Centre for Geosciences].

operational or commercial activities over the past two and a half decades. My congratulations to the entire ESTO team for this significant accomplishment. To read more about ESTO's origin, history, and recent scientific accomplishments, turn to page 7 of this issue.

In other news, the Terra/Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) Science and Instrument Teams have been selected as the recipient of the 2023 American Astronautical Society (AAS) Earth Science and Applications Award. The award is presented annually for an outstanding achievement in Earth or environmental sciences. The team is being recognized for development of a pioneering instrument onboard NASA's Terra and Aqua satellites, which has revolutionized our understanding of Earth's dynamic processes and global environmental changes. My sincere congratulations to the Terra and Aqua MODIS teams.

Finally, NASA had another excellent exhibit at the American Geophysical Union (AGU) Fall Meeting in San Francisco, CA this past December. NASA's multidecadal exhibit presence at the annual AGU Fall Meeting has been coordinated for many years by GSFC's Science Support Office (SSO). Nearly 40 NASA projects and missions had hands-on activities within the perimeter of the NASA Science exhibit – from the James Webb Space Telescope to the Airborne Science Fleet. The **NASA Hyperwall**, a video wall used for visual-forward science storytelling, served as the backdrop for 57 Hyperwall Stories throughout the meeting, including 8 presentations delivered by the 2023 winners of the NASA-funded *AGU Michael H. Freilich Student Visualization Competition*. The exhibit also featured 44 tech demos throughout the week, covering a wide range of hands-on introductions to everything from the capabilities of the OpenSpace data visualization software to the scientific applications of augmented reality. To read more about the NASA Science exhibit at AGU, turn to page 12 of this issue. ■

In Memoriam: Dr. Richard S. Stolarski [1941–2024]

Photo. Dr. Richard (Rich) Stolarski in February, 1989 at the NASA Arctic Airborne Stratospheric Experiment (AASE-I) in Stavanger, Norway. Rich is seen here describing model results from the GSFC chemistry model. **Image credit:** Paul Newman/NASA

Renowned ozone scientist Dr. Richard "Rich" Stolarski died on February 22, 2024, at age 82 from the complications of prostate cancer. Rich was born at Fort Lewis, WA on November 22, 1941. After short stays in Kansas and Hawaii, Rich's family settled in Tacoma, WA. He attended Stadium High School for three years and Wilson High School for his final year. He received his Bachelor of Science in physics and mathematics from the University of Puget Sound in 1963 and his Ph.D. from the University of Florida three years later in 1966 under Professor Alex Green. Rich was a University of Michigan post-doctoral fellow from 1967 – 1974 under Professor Andrew Nagy, where he met his colleague and friend Dr. Ralph Cicerone.

Rich joined NASA in 1974 at the Manned Space Center (now the Johnson Space Center) as a research physicist in the Environmental Effects Projects Office. He moved to NASA's Goddard Space Flight Center (GSFC) in 1976 to join the fledgling Stratospheric Physics and Chemistry Branch. Rich was branch head (1979 – 1985) and a research scientist (1985 – 2010). He was the Program Scientist for the Atmospheric Effects of the Stratospheric Aircraft program at NASA headquarters from 1992 to 1995. From 2010 until his passing, Rich was a NASA Goddard Emeritus scientist and a Research Professor in the Department of Earth and Planetary Sciences at Johns Hopkins University.

Rich's atmospheric science career began during a period of great ferment. A proposed fleet of supersonic transport aircraft (SSTs) was being researched in the early 1970s, and scientists had proposed that nitrogen emissions from SST engines could deplete the Earth's ozone layer. In 1974, Rich and Ralph Cicerone published their groundbreaking paper showing that reactive chlorine compounds derived from emissions by the NASA space shuttle could also deplete the ozone layer. Mario Molina and Sherry Rowland independently proposed that reactive chlorine could destroy ozone, and further hypothesized that human-produced chlorofluorocarbons (CFCs) would be a source of reactive chlorine compounds. Molina and Rowland shared the 1995 Nobel Prize in chemistry for this work, and Stolarski and Cicerone were cited in the Royal Swedish Academy of Science's press release for their contributions. Rich was awarded the United Nations Environmental Program's **Ozone Award in 1997**, where "Dr. Ralph J. Cicerone and Dr. Richard S. Stolarski were the first to indicate the important role of chlorine monoxide in stratospheric ozone depletion."

The severe ozone decline over Antarctica discovered by British Antarctic Survey scientists in the 1980s was simultaneously shocking, disturbing, and exciting. In parallel, Dr. P. K. Bhartia and others were examining extremely low ozone values measured by the Total Ozone Mapping Spectrometer (TOMS) aboard NASA's Nimbus–7 satellite. Rich and colleagues found that TOMS showed that this severe Antarctic ozone decline was continental in scale, publishing the first paper on satellite observations of this ozone depletion. This rapid ozone decline combined with the continental scale led to the coining of the name "Antarctic Ozone Hole" to describe the phenomenon. The ozone hole's appearance did not directly lead to the finalizing of the "Montreal Protocol on Substances that Deplete the Ozone Layer" (now signed by every nation on Earth), but it likely influenced negotiations for the treaty and supported later strengthening of the protocol with amendments in 1990 and 1992. Subsequent work showing that chlorine-containing substances were causing the ozone hole led to a complete banning of CFCs in 2010. Rich's work on the Antarctic ozone hole was cited in his 2007 NASA Goddard Scientific Research Award as "… one of the most important papers in atmospheric science in the second half of the twentieth century." Rich also received NASA's Exceptional Achievement Medal for his ozone hole research and was named a Fellow of the American Geophysical Union in 1996.

Rich continued his ozone layer research, contributing to the development of trend-quality data sets. In 1991 he published a seminal paper on ozone trends that showed the unambiguous decline of the ozone layer. In this paper he carefully removed "natural" ozone variations to reveal a steady downward ozone trend. Rich was recognized in 1991 by the U.S. Environmental Protection Agency's Ozone Protection Award for being "… a leader in the verification of ozone depletion from observational data."

Assessments of ozone depletion are written reports from scientists that provide the foundation for the international Montreal Protocol and Vienna Convention. While many "national" reports were written following Rich's 1974 paper, there was no international consensus. In December 1980, Rich led an international-based scientific summary of the stratosphere and an assessment of human impact on the ozone layer. This was followed by the 1985 three-volume international report (**Atmospheric Ozone: 1985**) in which Rich helped write the introduction as well as provide model contributions, reviews, and edits of the report. *Ozone 1985* was the scientific basis for the landmark Montreal Protocol. Rich contributed to assessments in 1988, 1989, 1991, 1994, 1998, 2002, 2006, 2010, and 2014 in several roles. Rich attended many of the Les Diableret meetings where the primary executive summaries for Montreal Protocol policy makers were written. Rich's calm influence and careful science statements at those meetings helped produce clear and consistent messages for the nations of the world in their Montreal Protocol deliberations.

Rich's modeling contributions began with one dimensional models (height) in the 1970s, evolving to height – latitude models in the 1980s, and fully three-dimensional models late in his career. He was expert at identifying the processes that controlled the simulated ozone distribution and its response to natural and human-produced perturbations. Late in his career at NASA, Rich took on the challenge of leading NASA Goddard's chemistry–climate modeling project. Rich applied his strengths to this project, making sure that it focused on the scientific questions of the day and examining how ozone changes impact the temperature and dynamics of the stratosphere and troposphere. In 2009, Rich was awarded the NASA Robert H. Goddard Award of Merit, in part for having "… pioneered a new initiative in the model of the coupling of chemistry and climate, utilizing the GMAO climate model, and involving a large number of Goddard and outside scientists."

In the 1990s the World Climate Research Program's (WCRP) Stratospheric Processes effort was emerging, drawing together scientists from many nations to discuss our evolving understanding of the ozone layer. As an important contributor to conferences and summer schools organized by this WCRP effort, Rich could be found in the center of a crowd of early career scientists, discussing ozone, science, and life, thus fostering the next generation of leaders. He was elected a member of the International Ozone Commission (IO3C) in 1996, became the IO3C vice-president in 2008, and was elected as an "Honorary IO3C Member" in 2016.

Papers, citations, and awards are performance measures that rarely fully capture the totality of a scientist's contribution and clearly fail to capture the essence of a life. Rich had an extremely distinguished science career with 155 publications in refereed science journals and 63 additional publications in other reports and science documents. Rich was a quick thinker with a curiosity and a love of learning that never faded. He was particularly adept at the use of models and analysis to identify the processes that control the ozone distribution, the interplay between chemical reactions and transport, and applying his knowledge to understand the stratospheric response to anthropogenic changes in composition and climate. He was a selfless contributor and an excellent collaborator. He was a friend and mentor to many, and through his mentorship his legacy will continue.

In addition to his scientific family, Rich is survived by his beloved wife of 59 years, Shirley Stolarski; daughter Susan Stolarski Datta and her husband Joy of Charleston, SC; son Steven Stolarski and his wife Vanessa of Purcellville, VA; three grandchildren, Kellen Datta, and Zachary and Maxwell Stolarski; brother Bob Stolarski and his wife Jean of Dewey, AZ; and brother-in-law Bob Jewett and his wife Janet of Loveland, CO.

Acknowledgments: *The Earth Observer* staff wishes to thank **Paul A. Newman** [GSFC] and **Anne Douglass** [GSFC, *emeritus*] for writing this *In Memoriam*. ■

NASA's Earth Science Technology Office Celebrates 25 Years

Philip Larkin, Earth Science Technology Office, Philip.larkin@nasa.gov

Introduction

Many Earth science missions, both airborne and on orbit, can trace their origins to the early technology developments that produced the groundbreaking instruments, instrument *components* (the parts or subsystems that make up an instrument), and information systems that enabled these missions. To give one recent example, NASA's **Plankton, Aerosol, Cloud, ocean Ecosystem mission (PACE)** mission, launched on February 8, includes two instruments – the **Ocean Color Instrument** and the **Hyper-Angular Rainbow Polarimeter #2** – that were directly derived from technology development efforts.

Since 1998, NASA's **Earth Science Technology Office** (ESTO) has been the entity the fullfills this technology testing and development function within NASA's Earth Science Division.[1] March 15, 2023, marked the twenty-fifth anniversary of ESTO. As with many organizations, the quarter-century milestone is a natural time to reflect on the past and look toward the future.

Following an opening historical overview of ESTO, the majority of the article summarizes a 2023 analysis of the ESTO portfolio of investments, taking a retrospective look at the accomplishments from the first 25 years.

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Overview of ESTO History

By the 1990s, NASA Earth Science recognized that untested and underdeveloped technologies had the potential to stall the progress of mission implementation, occasionally idling large mission teams while bugs were worked out. (For context, this would be around the time the first missions of the Earth Observing System (EOS) were preparing to launch.) ESTO was formed to help manage and nurture technologies outside of the framework of flight missions, to allow new ideas to incubate and mature fully before being picked up for operational use.

Since its inception, ESTO has employed an open, flexible, science-driven strategy that relies on competition and peer review to select promising technologies for Earth science. While early efforts focused on remote sensing instruments and data systems, solicitation topic areas gradually expanded to span the diversity of needs and requirements, from lidar and sensor webs to efforts that focus on a particular science theme, e.g., wildfire science and mitigation.

Over the last 25 years, ESTO has awarded and managed more than 1100 technology projects for future science measurements. This forward-looking portfolio has enabled new Earth-observing capabilities, informed Earth Science Decadal Surveys and strategic planning, and generated numerous infusions and spinoffs.

While every technology project has a story to tell, ESTO has assembled a series of 30 highlights focusing on some of the more notable impacts. Visit the dedicated **25th Anniversary Project webpage** to learn about some of the most notable ESTO technologies that have been infused into Earth science missions, science campaigns, or other operational or commercial activities over the past quarter century.

[1] To learn more about the components of ESTO, see **ESTO: Benfitting Earth Science Through Technology**, in the May–June 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 3**, pp. 22–29].

Twenty-fifth Anniversary Analysis

In 2023, ESTO undertook a review of its portfolio to catalog past achievements. The results compiled to date are summarized in the subsections that follow. Taken together, they clearly show the remarkable impact of ESTO's 25 years of early, deliberate technology development to Earth science as well as other space science and commercialization activities.

A Diversified Portfolio

ESTO technology projects find their origins in a wide range of people and institutions across the country. Principal Investigators (PIs) hail from more than 200 different organizations – from colleges and universities to corporations and non-profits to NASA field centers and Federal labs – in 42 states. More than 2000 collaborators, co-investigators, and other partners also contribute their expertise, from over 400 organizations in 44 states – see **Figure 1**.

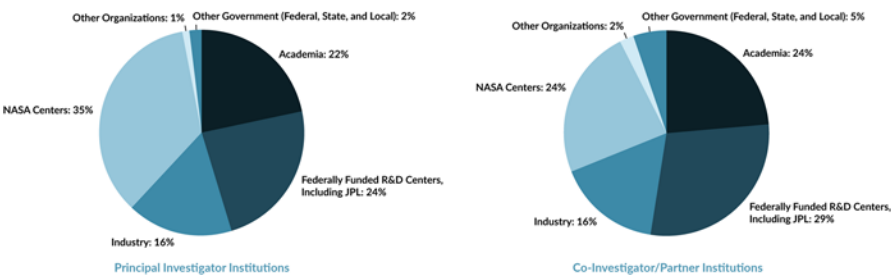

Figure 1. Breakdown of organization affiliations of ESTO PIs and Co-PIs. **Image credit:** Philip Larkin/GSFC

In response to the 44 solicitations ESTO has released since 1998, this community of technologists, engineers, and scientists has supplied an abundance of new ideas and methods for NASA Earth science endeavors. The ESTO portfolio addresses the full breadth of Earth science measurements, from remote sensing instruments and instrument subsystems to advanced information systems, machine learning, and modeling to highly targeted areas such as quantum sensing, wildfire technologies, and Earth digital twins. New technologies on orbit, in the air, and on the ground are helping to improve Earth System science measurement processes, from predictions to observations and initial data collection to analysis and information access.

Measuring Advancements

ESTO makes regular assessments of Technology Readiness Levels (TRLs) for most projects in the portfolio, including at the outset of the project, at the final review, and at least annually during the period of funding. (Some projects, particularly studies and operational transition efforts, are not assigned TRLs). The TRL scales – see **Figure 2** – provide a useful framework to evaluate the current state of a technology as well as track development progress over time.

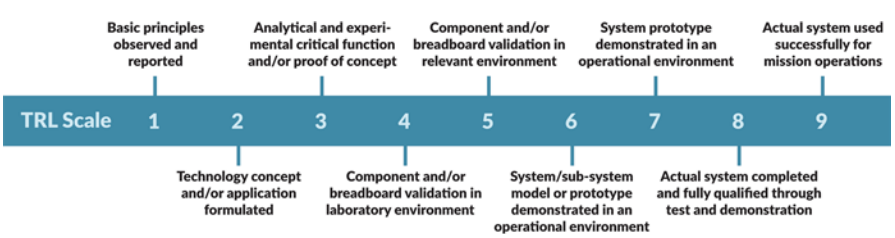

Figure 2. The ESTO Technology Readiness Level (TRL) scale helps track the development of most projects in its portfolio. ESTO has been successful in advancing many of its projects by one or more TRLs throughout their lifetime – see **Figure 3** on page 9. For example, 31% of projects active in 2023 advanced by at least one TRL. **Image credit:** Philip Larkin

In 1998, the NASA Earth Science Division set a goal for ESTO to annually advance 25% of currently funded technology projects at least one TRL. This metric has been surpassed every year since. For example, in Fiscal Year 2023 (FY23), 31% of active ESTO projects advanced at least one TRL. An analysis of all the TRL-reportable projects that have graduated from ESTO funding yields a more complete and impressive picture of advancement – see **Figure 3** and **Figure 4**. In short, these Figures show that most projects that go to ESTO with the goal of maturing technology do in fact do so.

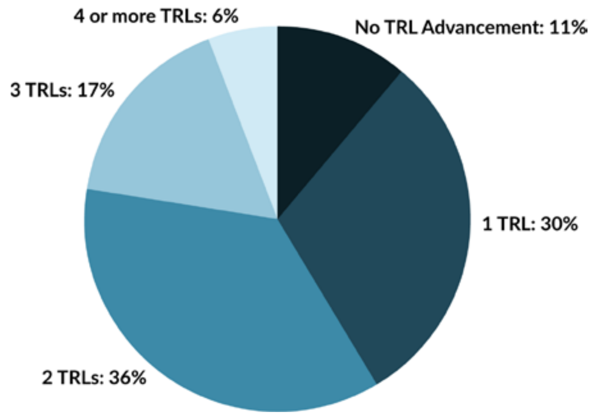

Figure 3. Nearly 90% of the 812 projects that have graduated from ESTO funding and were assessed for TRL have advanced one or more levels. **Image credit**: Philip Larkin

Infusions and Transitions By the Numbers

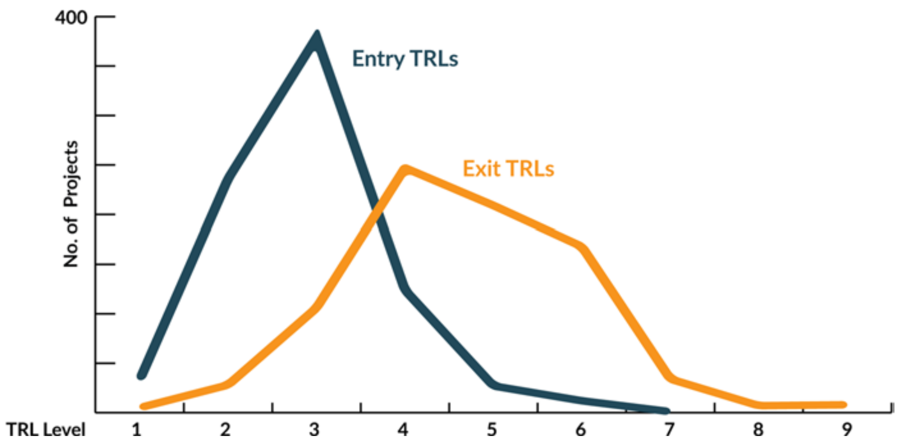

Figure 4. The chart shows the overall distribution of start (blue curve) and end (orange curve) of of the 812 completed TRL projects. TRL distributions also vary by ESTO program area; components generally have lower entry and exit TRLs than instruments, for example. **Image credit:** Phiip Larkin

ESTO PIs have reported at least 269 infusions of their technologies into Earth science missions, science campaigns, and other operational or commercial activities. The breakdown of verified infusions since 1998 includes:[2]

- 65 projects integrated into Earth science flight missions operated by NASA and/or its domestic or international parners;
- 43 projects integrated into non-Earth science flight missions;
- 44 projects integrated into NASA Earth Venture (EV) missions – including Suborbital (EVS), Instrument (EVI), Mission (EVM), Continuity (EVC), and Instrument Technology (EVIT);
- 52 projects integrated into airborne science campaigns;
- 56 projects integrated into NASA Distributed Archive Data Centers; and
- 9 projects transitioned into commercial applications.

The transition of ESTO technologies to other sources of funding for further development also occurs regularly. Several hundred projects have transitioned to other NASA programs, other Federal agencies, Small Business Innovation Research (SBIR) awards, or internal funding through the originating organization. ESTO initiated a study in 2023 to further codify these transitions to better understand the paths taken by technology efforts, both before and after ESTO investment.

[2] The **orginal ESTO acticle** includes these same bullet points along with a comprehensive list of examples of the missions, campaigns, or other activities included under this category of technology infusion.

Publications and Presentations

Just as with basic science research, the sharing of ideas and findings is crucial to the advancement of technology. To date, more than 600 articles on ESTO technologies have appeared in peer-reviewed journals, including in *Science*, *Nature*, the *Proceedings of the National Academy of Sciences*, *Environmental Science and Technology*, and various journals from the *Institute of Electrical and Electronics Engineers* (IEEE). These numbers are even more impressive, considering that in the early years of the office, many projects were not documented in journal articles.

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Conference papers and presentations by ESTO projects – at meetings convened by the American Geophysical Union, the American Meteorological Society, the International Society for Optics and Photonics (SPIE), IEEE, and others – number well above 2500 and, as with journal citations, are undercounted historically.

Since 2001, ESTO has also hosted a nearly annual conference. Now known as the **Earth Science Technology Forum** (ESTF), the meeting presents an opportunity for PIs to further showcase their work. There have been 19 iterations of this event held during the last 23 years, generating some 1300 presentations to more than 5000 attendees. The **2024 ESTF** has been scheduled for June 11–12, 2024, in Crystal City, VA.

Patents

At least 23 patents have been issued for ESTO technologies. An example from 2023 is *Integrated Multiwavelength Wavelength Division Multiplexing (WDM) Time Division Mutliplexing (TDM) Lidar Transmitter* from **Guangning Yang** and **Jeffrey Chen** [both at NASA's Goddard Space Flight Center] (**Patent Number: US 11,493,602 B1; Issued: 11/08/2022**).

Students

As with many research and development activities, students are integral to the work and success of technology development teams. Since ESTO's founding, at least 1180 students from 171 institutions have worked on various ESTO-funded projects. Aided by their experiences, students who take part in these projects have often gone on to work in the aerospace industry and in related fields. As an example, the **Photo** below shows students involved in the 2019 ESTO–Amazon Web Services (AWS) **DeepRacer Challenge**.

In Fiscal Year 2023 alone, at least 157 students from 48 institutions were involved with active technology development projects. Typically, these students are pursuing

Photo. Student teams and their mentors at the 2019 NASA DeepRacer Challenge, a collaborative event between ESTO and Amazon Web Services. The teams developed machine learning algorithms to control and steer toaster-sized autonomous cars around a track. **Image credit:** Paul Padgett/NASA undergraduate and graduate degrees, but occasionally high school students also have had the opportunity to participate.

Conclusion

Although often separated by years or decades from the missions and science they enable, technology developments remain a critical first step in NASA's Earth Science endeavors. Many of the projects being awarded today will lead to new capabilities in the 2030s and beyond; some in revolutionary ways and others as incremental steps in a continuum of observations. Still others will "fail" or be overcome by alternative approaches, imparting lessons about feasibility and informing alternative paths forward. ESTO is committed to continuing its careful approach to technology development for the next quarter century and looks forward to facilitating the next generation of Earth science measurements. ■

Earth Science Meeting and Workshop Calendar

NASA Community

May 14–16, 2024
CERES Science Team Meeting
POC: **norman.g.loeb@nasa.gov**
Hampton, VA

June 3–6, 2024
OMI–TROPOMI Science Team Meeting
Boulder, CO

Global Science Community

April 14–19, 2024
European Geosciences Union (EGU) General Assembly
Vienna, Austria

May 17–22, 2024
American Thoracic Society International Conference
San Diego, CA

May 26–31, 2024
Japan Geoscience Union (JpGU) Annual Meeting
Chiba, Japan

May 29–31, 2024
Second Workshop on Remote Sensing in Oxygen Absorption Bands
De Bilt, The Netherlands

June 3–6, 2024
CFMIP/CLIVAR Meeting on Clouds, Circulation, and Climate
Boston, MA

June 4–6, 2024
CALIPSO International Symposium on Spaceborne Lidar
Saint-Malo, France

June 10–12, 2024
NASA Goddard Workshop on the Use of Climate Models in Satellite Mission Design
New York, NY

June 17–21, 2024
IEEE International Radiation Symposium
Hangzhou, China

June 23–28, 2024
Asia Oceania Geosciences Society (AOGS) Annual Meeting
Pyeongchang-gun, Gangwon-do, South Korea

July 7–12, 2024
International Geoscience and Remote Sensing Symposium (IGARSS)
Athens, Greece

July 7–12, 2024
9th Global Energy and Water Exchange (GEWEX) Open Science Conference
Sapporo, Japan

July 14–19, 2024
19th International Conference on Clouds and Precipitation (ICCP)
Jeju, South Korea

July 15–18, 2024
11th International Precipitation Working Group (IPWG) Meeting
Tokyo, Japan

August 4–9, 2024
Ecological Society of America (ESA) Annual Meeting
Long Beach, CA

Seeing "Through the Eyes of NASA" at the 2023 AGU Annual Meeting

Nathan Marder, NASA's Goddard Space Flight Center/Global Science & Technology Inc., nathan.marder@nasa.gov

Introduction

As one navigates the global constellation of scientific conferences offered each year, the annual Fall Meeting of the American Geophysical Union (AGU) is the guiding star. The meeting attracts participants from an ensemble of academic disciplines and a sizeable number from private industry. This diverse crowd converges each year to share ideas, research, and technological advancements in geophysics and its commensurate fields of Earth and space sciences.

The 103rd installment of the meeting in 2023 proved to be no exception. Attendance soared to pre-pandemic levels, as 24,843 individuals from more than 100 countries convened December 11–15, 2023, at the Moscone Convention Center in San Francisco, CA. This past year's event (AGU23) continued the hybrid format that began out of necessity during the pandemic and has now become the "new normal" for many meetings. A selection of the meeting's plenary sessions, posters, and exhibitor booths were available online, providing those who couldn't attend the in-person conference with an option for virtual, on-demand participation.

NASA's Science Support Office (SSO) continued its longstanding role of leading the planning and logistics for the NASA exhibit at the Fall AGU. SSO hosted a series of planning telecons leading up to the meeting and oversaw the design, construction, and staffing of the NASA Science exhibit, which enjoyed "prime real estate" at the heart of the Moscone West exhibit hall. Over 100 NASA scientists and outreach coordinators from all five scientific divisions of the Science Mission Directorate (SMD) – which include Earth Science, Planetary Science, Heliophysics, Astrophysics, and Biological and Physical Sciences – staffed the NASA exhibit throughout the week. The scientists and outreach coordinators used NASA Science products and activities to engage, inform, and inspire AGU attendees – see **Photo 1**.

NASA's Science Support Office (SSO) continued its longstanding role of leading the planning and logistics for the NASA exhibit at the Fall AGU.

Altogether, nearly 40 NASA projects and missions had hands-on activities set up within the perimeter of the NASA Science exhibit – from the **James Webb Space Telescope** to the **Airborne Science Fleet**. To encourage participants to "play" with NASA content contained within the exhibit playpen, each person (or group) received a passport as they entered. The passport identified six hidden images – in this case, all six posters from the **Science Explorers Poster Series** – strategically placed within the exhibit's perimeter. The task was simple: for each poster found, participants would receive a corresponding stamp. Once a certain number of stamps were collected, participants could then present their completed passports to the Information Table and take home some NASA products (bags, lenticulars, lithographs, posters).

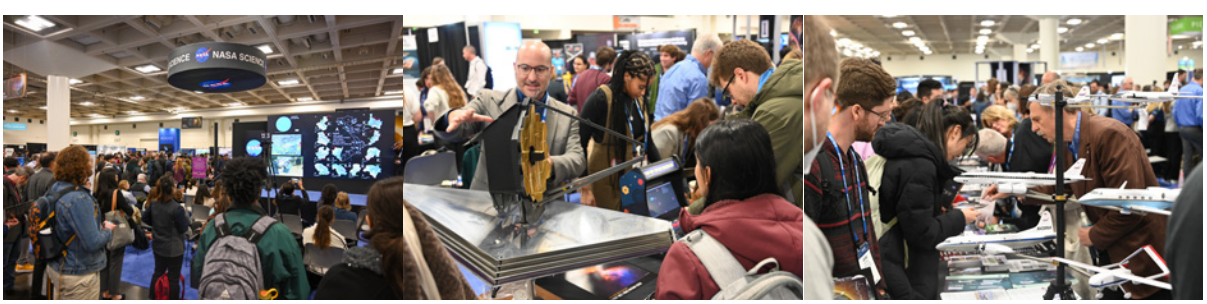

Photo 1. [*left*] The NASA Science exhibit at AGU23 as viewed from the front of the NASA Hyperwall, where attendees gathered throughout the week to watch presentations delivered by NASA scientists and agency partners. [*middle*] Outreach personnel from NASA's Astrophysics Division discuss the James Webb Space Telescope in front of a scale model of the telescope. [*right*] A collection of project scientists and outreach specialists interact with AGU attendees at the NASA Science exhibit tables. **Photo credit:** NASA

The remainder of this article attempts to capture the flavor of the weeklong meeting in images and words. A selection of Hyperwall Stories from **NASA SMD leadership** and the student winners of the **Michael Freilich Student Visualization Competition** are now available for on-demand viewing.

Annual SMD Strategic Content and Integration Meeting

Ahead of AGU23, interdivisional communications teams met on December 10, 2023, to discuss and coordinate NASA Science's content strategy for the coming year. During the hybrid meeting, approximately 130 in-person and 55 online NASA employees discussed effective communication strategies and workflows for the coming year.

During the event, NASA employees presented on international partnerships and communication campaigns that align with 2024 engagement and outreach strategies – see photo below. In addition, the all-day event featured an "Ask Us" panel discussion with NASA SMD Division Directors, an update on the agency's SMD-specific websites, improvements to the NASA Science exhibit presence, and plans for the upcoming total solar eclipse. There were breakout sessions held for Earth Science, Planetary Science, and Heliophysics personnel, during which participants discussed priorities, ideas, and strategies for the year ahead.

[*top Left*] NASA Science teams meet at the San Francisco Marriott Union Square for the annual Strategic Content and Integration Meeting. [*top right*] Members of NASA Science leadership facilitate an "Ask Us" panel to discuss the outcomes from the Strategic Content and Integration Meeting. [*bottom*] Outreach personnel and leadership from NASA's Heliophysics Division pause for a photo during a breakout session. **Photo credit:** NASA

Ahead of AGU23, interdivisional communications teams met on December 10, 2023, to discuss and coordinate NASA Science's content strategy for the coming year.

NASA Hyperwall Stories

The NASA Hyperwall served as the backdrop for **57 Hyperwall Stories** at the meeting, including 8 presentations delivered by the **2023 winners** of the AGU Michael Freilich Student Visualization Competition. NASA leadership took to the stage shortly after the exhibit floor opened to attendees on December 11. **Nicola Fox** [NASA HQ—*Associate Administrator of SMD*] shared a panoramic view of the 2024 research goals of NASA Science and wowed the audience with a dazzling series of science images from the previous calendar year – see **Photo 2**.

In addition, **Karen St. Germain** [NASA HQ—*Director of the Earth Science Division*], **Lisa Carnell** [NASA HQ—*Director of the Biological and Physical Sciences Division*], **Mark Clampin** [NASA HQ—*Director of the Astrophysics Division*], **Lori Glaze** [NASA HQ—Director of the Planetary Science Division], and **Mark Subbarao** [NASA

Goddard Space Flight Center—*Director of the Scientific Visualization Studio*] delivered opening-day presentations. **Photos 3–6** give more details on each of these presentations.

Photo 2. Nicola Fox [NASA HQ—*Associate Administrator of SMD*] provides an overview of NASA's Heliophysics Division in front of the Hyperwall, sharing a photo of the Sun captured by NASA's Solar Dynamics Observatory. **Photo credit:** NASA

Peg Luce [NASA HQ—*Deputy Director of the Heliophysics Division*], **Nicki Rayl** [NASA HQ—*Associate Director for Flight Programs, Heliophysics Division*], and **Gina DiBraccio** [NASA's Goddard Space Flight Center (GSFC)—*Project Scientist for the Heliophysics Division*] officially introduced **Joseph Westlake**, the newly appointed Director of NASA's Heliophysics Division – shown in **Photo 7** on page 15 – as part of a presentation entitled "The Heliophysics Big Year."

Photo 3. Karen St. Germain [NASA HQ—*Director of SMD's Earth Science Division*] delivers her Hyperwall presentation, titled "An Overview of NASA Earth Science," which gave an overview of NASA's Earth Science fleet and focused on upcoming mission launches. **Photo credit:** NASA

Photo 4. Lori Glaze [NASA HQ—*Director of SMD's Planetary Science Division*] gave a presentation that focused on the success of the OSIRIS-REx mission, which is the first mission to successfully return a sample from another celestial object (**101955 Bennu,** a near-Earth asteroid) to Earth, and also previewed upcoming Planetary Science missions. **Photo credit:** NASA

Photo 5. Mark Clampin [NASA HQ—*Director of SMD's Astrophysics Division*] discusses the state of NASA's broad suite of astrophysics missions and research goals. **Photo credit:** NASA

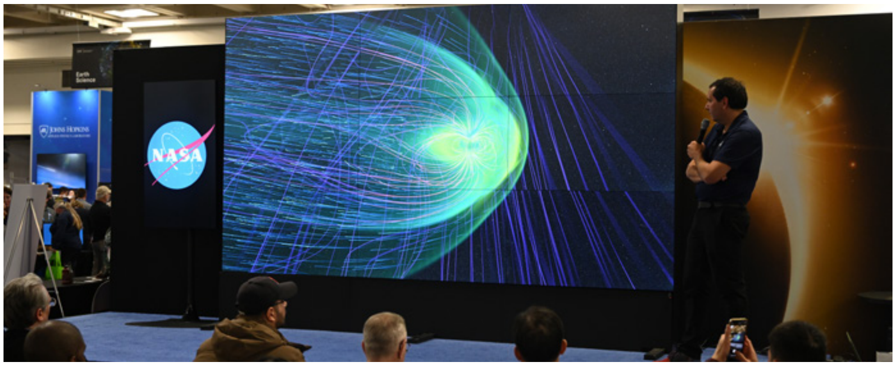

Photo 6. Mark Subbarao [GSFC—*Director of NASA's Scientific Visualization Studio*] discusses the studio's latest data visualization efforts and shares some of the most recently produced visualizations. **Photo credit:** NASA

Other Hyperwall Stories presented throughout the week focused on topics such as NASA's **Earth Information Center**, a first look at NASA's **Surface Water and Ocean Topography** (SWOT) satellite, the success of NASA's **OSIRIS–REx sample return mission**, NASA's **Nancy Grace Roman Space Telescope**, and an overview of space experiments conducted by SMD's Biological and Physical Sciences Division.

Photo 7. Joseph Westlake [NASA HQ—*Director of the Heliophysics Division*] addresses an audience of AGU attendees from the NASA Hyperwall stage. **Photo credit:** NASA

Other Highlights from the NASA Science Exhibit

Every December, AGU bookends the Science Support Office's annual conference schedule – serving as a culmination of the year past and providing a blueprint for the year ahead. At AGU23, NASA Science unveiled its strategic messaging and artwork for the 2024 calendar year with the theme, "Through the Eyes of NASA." The "Through the Eyes of NASA Photowall" at the NASA exhibit was intended to help promote the 2024 theme for conference attendees – see **Photo 8**. It featured a three-dimensional display based on the artwork of **Jenny Mottar** [NASA HQ—*SMD Art Director*].

"This year's artwork was inspired by the *Heliophysics Big Year*, which began with the Annular Eclipse this past October and concludes with the upcoming total solar eclipse on April 8, 2024," said Mottar. "I wanted to capture what it feels like to experience the beauty of nature – that perfect moment where you wish you could freeze time."

Photo 8. An image of the "Through the Eyes of NASA" photowall, featuring artwork from **Jenny Mottar** [NASA HQ—*SMD Art Director*]. **Photo credit:** NASA

As the visual keystone of NASA's exhibit presence, the 10' x 20' photowall gave AGU attendees a chance to interact with the 2024 theme and immerse themselves in the world of NASA Science. Exhibit staff and AGU attendees alike delighted at the opportunity to pose in front of the wall with friends and colleagues – see **Photo 9**.

Photo 9. Members of NASA's Global Learning and Observation to Benefit the Environment (GLOBE) program and AGU attendees pose with NASA props in front of the "Through the Eyes of NASA" photowall. **Photo credit:** NASA

The **2024 NASA Science planning guide**, (a 14-month calendar featuring an image from one of SMD's five divisions for each month) also features Mottar's artwork and is available for digital download in the NASA Science Multimedia Gallery. The Fall AGU is typically one of the first events at which the new year's planning guide is available, so it is an extremely popular item. NASA Science worked with AGU to coordinate distribution of 6500 Spanish and English-language planning guides at the 2023 Fall AGU meeting. AGU staff assisted with distribution of the planning guides, which were dispensed daily at the entrance to the Moscone West exhibit hall – see **Photos 10–11** – along with 22,000 pairs of NASA Science eclipse glasses to promote safe viewing of the April 8, 2024, total solar eclipse.

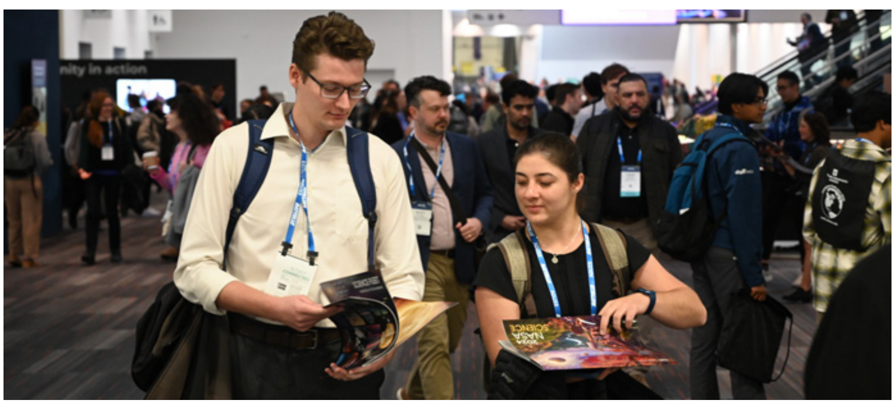

Photo 10. AGU attendees explore their copies of the coveted 2024 NASA Science Planning Guide as they arrive at the Moscone West exhibit hall. **Photo credit:** NASA

Photo 11. A collection of 2024 NASA Science Planning Guides are organized near the entrance to the Moscone West exhibit hall. **Photo credit:** NASA

The planning guides and glasses were placed at a prominent location at the front of the exhibit hall to ensure attendees had access to the robust lineup of activities and products available at the NASA Science exhibit. A group of 115 subject matter experts from all five SMD divisions engaged AGU attendees with a collection of NASA products, handouts, interactive activities, three-dimensional models, and demonstrations – see **Photo 12**.

Photo 12. [*left*] A model of the surface of Jupiter's moon Europa inspires AGU attendees to learn more about NASA's planetary science missions and research. [*middle*] **Mike Taylor** [GSFC/Science Systems and Applications, Inc. (SSAI)—*Outreach Scientist*] shares information with AGU attendees about Landsat satellite data and uses the Science and Technology Education for Land/Life Assessment handheld spectrometer, or STELLA, to demonstrate how NASA scientists study plant health from space. [right] NASA Polarimeter to Unify the Corona and Heliosphere (PUNCH) team members demonstrate how to make a pinhole projector in preparation for the April 2024 solar eclipse. **Photo credit:** NASA

The exhibit also featured **44 tech demos** – **see Photo 13** – throughout the week, covering a wide range of topics. Attendees gathered in small groups at the top of each hour near two demo kiosks for hands-on introductions to everything from the capabilities of the OpenSpace data visualization software to the scientific applications of augmented reality. See the schedule for more details on the demos.

Photo 13. [*top left*] **Carter Emmart** [OpenSpace—*Creative Lead*] conducts a tech demo on the capabilities of the data visualization software. [*top right*] **Steve Graham** [GSFC/Global Science and Technology Inc.—*Outreach Specialist*] participates in a tech demo covering the use of augmented reality by NASA engineers to study and interact with scaled models of the Dragonfly and Perseverance Mars Rovers. [*bottom*] **Jason Craig** [NASA JPL—*Technical Producer and Manager, NASA's Eyes*] intrigues AGU attendees with a demonstration of the primary features and applications of the visualization software. **Photo credit**: NASA

A steady stream of spirited attendees visited the NASA booth during exhibiting hours (10:00 AM to 5:00 PM daily) but it was the six scheduled signings of the **Science Explorer Poster Series** that garnered the most attention. Each art design reflects a distinct thematic focus of prominent NASA Science missions and research goals. AGU attendees organized themselves along the perimeter of the NASA Science exhibit, waiting for their turn to meet, take photos with, and collect artwork signed by Mottar – see **Photo 14**. In total, there were 6000 posters signed and distributed to attendees over the course of the week.

Photo 14. SMD Art Director **Jenny Mottar** interacts with AGU attendees during one of six scheduled Science Explorer poster signings. **Photo credit:** NASA

Conclusion

By establishing a multi-decade exhibit presence at what is arguably the gold standard in scientific conferences, NASA Science research, products, and Hyperwall stories have engaged hundreds of thousands of AGU attendees and played a fundamental role in the organization's effort to inspire, accelerate, and punctuate the importance of geophysical sciences and its related fields.

Building on the success of AGU 2023, the NASA Science Support Office is committed to enhancing NASA's ability to engage, inspire, and empower a diverse audience of scientists, students, and members of the general public in 2024 and beyond. NASA Science will exhibit at more than 30 domestic and international conferences in 2024, concluding with AGU24, which will take place December 9–13, 2024, in Washington, DC. ■

Summary of the 2023 GRACE Follow-On Science Team Meeting

Felix Landerer, NASA/Jet Propulsion Laboratory, landerer@jpl.nasa.gov

Introduction

In October 2023, the annual gathering of the **Gravity Recovery and Climate Experiment** (GRACE) and GRACE Follow-On [G-FO] Science Team took place in Boulder, CO, hosted at University Corporation for Atmospheric Research's (UCAR) Center Green campus. The event had 70 in-person participant and an additional 52 online participants – see **Photo**. G-FO is a U.S.–German collaboration between NASA and the Helmholtz Centre Potsdam GeoForschungsZentrum (GFZ) [German Research Centre for Geosciences].

The meeting agenda featured 15-minute presentations over three days, describing new findings from G-FO observations and the combined GRACE and GRACE-FO [G/G-FO] climate data record that now spans over 21 years (2002–2023).

The meeting began with the customary G-FO project status session, covering programmatic mission and flight segment technical updates, future mission plans, and descriptions of the latest data released from the GRACE Science Data System (SDS) centers. Subsequent sessions featured more than 53 contributed presentations covering analyses, algorithms, and science results by Science Team members and attendees, totaling 57 oral and 5 poster presentations. **Many of the presentations** are posted on the GRACE website. While this summary will cover all the content on the agenda of the meeting – it does do so in an exact linear fashion. It begins with a G-FO mission status update, followed by key highlights from the contributed analysis and science presentations.

Status of GRACE Follow-On

Since their launch on May 22, 2018, the twin G-FO satellites have been tracking Earth's water movements and global surface mass changes that arise from climatic, anthropogenic, and tectonic changes. G-FO also enables new insights into variations of ice sheet and glacier mass, land water storage, as well as changes in sea level and ocean currents. These measurements have important applications and implications for everyday life. The impact of these data is underscored by the **publication of over 6000 scientific papers** – an average of 5 new publications per week – that have established G/G-FO as a leading Earth Science mission.

In May 2023, G-FO successfully completed its Prime Mission phase that lasted five years after launch. G-FO was among the missions that went through the **2023 NASA Earth Science Senior Review**. The NASA project team submitted its response in spring of 2023 to extend mission operations through 2026. The proposal received overall Excellent score, highlighting the unique utility the data provide for Earth Science research and societal applications. However, the G-FO project's NASA budget will be reduced (compared to the previous baseline) by 15% in fiscal year (FY) 2024 and 24% in FY 2025 and 2026 due to the overall budget constraints that NASA is facing. The G-FO team remains confident in its ability to continue delivering high-value and high-impact science data products – prioritizing science operations management and data latency over data reprocessing campaigns. Both NASA and GFZ had already formally committed

Photo: Pictured here are the in-person attendees of the 2023 GRACE-FO Science Team. Another 52 people participated online. **Image credit:** Felix Landerer/JPL to extending their collaboration on G-FO mission operations and data processing through the end of 2026 via a Memorandum of Understanding.

As of December 2023, the G-FO project team has processed and released 62 monthly gravity fields – the most recent being for October 2023 (at the time of this writing). The primary mission objective for G-FO is to provide continuity for the monthly GRACE mass-change observations (2002–2017) via its Microwave Interferometer (MWI) intersatellite range-change observations. G-FO also demonstrated a novel technology demonstration Laser-Ranging Interferometer (LRI) for more accurate satellite-to-satellite ranging observations for future GRACE-like missions. The LRI has been successfully operated in parallel with the MWI for most of the mission, delivering excellent quality data. LRI-based monthly gravity and mass change fields covering the period from mid-2018 to mid-2023 have been made available by the SDS teams for further analysis and study by the science community.

Programmatic, Mission, and Operations Updates

The meeting began with **Frank Flechtner** [GFZ–*German G-FO Project Manager*] and **Felix Landerer** [NASA/Jet Propulsion Laboratory (JPL)—*U.S. G-FO Project Scientist*] giving welcoming remarks, followed by detailed assessments of the G-FO mission and operations status from the core SDS centers and flight operations teams.

GRACE Follow-On Project Status

Felix Landerer gave an overview of the G-FO satellites and the science data system performance. He reported that G-FO continues to meet its goal of extending the GRACE mass-change and gravity data record at equivalent precision and spatiotemporal sampling.

Since the previous STM in October 2022,[1] the overall G-FO science instrument performance has been stable, and the SDS team continued to deliver a gapless monthly data record to users ahead of schedule (on average, within 43 days instead of the 60-day requirement). Improving the data calibrations of the accelerometer measurements – which are noise contaminated on one of the two G-FO spacecraft – remains a core focus of the project SDS team. To this end, an improved calibration approach that reduced data errors by 10–20% has been developed and will be operationalized by the team in the coming months.

Landerer reported that, as forecasted, the current Solar Cycle 25 has gained in strength through 2023 and will continue to do so through 2024 before subsiding again. The resulting higher non-gravitational forces acting on the satellites need to be properly accounted for in the accelerometer data processing.

He also noted that small thruster leaks in the satellites cold gas propulsion system have been closely monitored since 2021. To ensure stable data collection and sufficient lifetime margin to achieve continuity with the proposed successor mission GRACE-Continuity, or GRACE-C (which is the new name for the **Earth System Observatory** Mass Change mission scheduled for launch no earlier than 2028),[2] the G-FO project team, in conjunction with guidance from the satellite manufacturer Airbus and the German Space Operations Center, decided to adjust the operational data collection mode of G-FO to a *wide pointing mode* – which means that the two spacecraft are allowed to deviate from their relative line-of-sight pointing by up to 2°, whereas the previous pointing angles were 100 times smaller. This operational change necessitates fewer thruster firings, which in turn reduces leaks and improves accelerometer calibrations – and thus leads to better overall science data quality. Due to the wide pointing, the LRI intersatellite ranging data collection has been suspended in this operational mode. However, the LRI instruments are still activated and fully functional. Landerer emphasized that reducing the leak ensures that the GRACE-FO mission will have sufficient fuel to remain operational up until GRACE-C launches.

Despite these operational challenges, Landerer said that the science data delivered by G-FO continues to provide excellent utility and insights into a rapidly changing Earth system. He briefly highlighted a few scientific and decision-support contributions and achievements of G-FO over the last year. These included:

- **Monitoring California Groundwater**. G-FO recorded the largest seasonal total water storage gains over California after the multiple atmospheric rivers made landfall during the 2022/2023 winter. Yet, peak water storage in May was below values observed 15–20 years ago – due to long-term, sustained groundwater declines. Going forward, the data will be invaluable to assess groundwater recharge rates and processes.

- **Observing Water Cycle Extremes: Droughts and Pluvials**. The G-GFO 20-year data record has been analyzed to show the increasing intensity of wet and dry extremes of the global water cycle, which increased as global temperatures rose.

- **Tracking Polar Ice Mass Loss**. G/G-FO measured net ice mass gains over Antarctica that began around 2021 due to snow accumulation mainly

[1] To learn more about this meeting, see **Summary of the 2022 GRACE Follow-on Science Team Meeting** in the January–February 2023 issue of *The Earth Observer* [**Volume 35**, **Issue 1**, pp. 28–35].

[2] DLR and NASA officially announced the new name, which was chosen to honor the legacy of the GRACE satellite series (GRACE and GRACE-FO), at the 2023 AGU Fall Meeting in December 2023.

in East Antarctica, which offset the unabated mass loss of the West Antarctic ice sheet.

Subsequent science presentations presented in-depth analyses of these and other findings in the dedicated science sessions, some of which are summarized below.

Landerer also highlighted the expanding portfolio of *open science*[3] contributions that the project team is supporting: ***Jupyter notebooks*** are part of an expanding **GRACE Open Science toolbox** with the goal to expand this toolbox with input from the Science Team and user community in the coming years. In addition, easy-to-use browser data portals at **JPL** and **GFZ** have been key to expand the science and applications user community that increasingly use the Level-3 and higher data products in decision support contexts (e.g., for drought monitoring and water resources management).

A series of status reports on programmatic G-FO mission operations, science operations, and SDS processing followed the opening presentations. **Krzysztof Snopek** [GFZ] reported on the ground and mission operations at the German Space Operations Center (GSOC), which is responsible for G-FO spacecraft operations. All essential flight operations, software updates, and planned calibrations were successfully scheduled and carried out by GSOC. **Himanshu Save** [University of Texas, Center for Space Research (CSR)] provided the science operations assessment. He described the evolving Solar Cycle 25 and its influence on the G-FO spacecraft, the mission's fuel budget, and adjusted operational procedures and modes (such as the already-mentioned 'wide' pointing mode). **Christopher McCullough** [JPL] reviewed the status of G/G-FO Level 1 processing at JPL, detailing additional improvements made in the accelerometer calibrations. The team is using the noisy accelerometer data on one satellite and retrieving improved science information from it.

A representative from each of the G-FO mission SDS centers – which includes JPL, GFZ, CSR, and GSFC – summarized the status of the latest gravity-field and mass change data products [RL06.X L2], including an overview of background dealiasing models and the GFZ GravIS portal,[4] the updated JPL *mascon* data product,[5] new data-processing strategies, e.g., via range acceleration [CSR], and the status of ancillary Satellite-Laser-Ranging (SLR) data processing and dedicated G/G-FO products [GSFC].

Following the project team's status presentations, there was a 30-minute session to answer questions from the science community and discuss in more detail the mission performance, near-term operations and data processing plans, as well as to gather suggestions and feedback from the community.

Science Presentations

The remainder of the sessions in the meeting were open-submission science sessions, each of which centered around different thematic topics, including: G/G-FO analysis techniques and next generation gravity mission (NGGM) concept studies, and science analysis of mass-transport data in the fields of glaciology, oceanography, hydrology, and solid-Earth physics. As has been the case in previous years, the presenters underscored the value of interdisciplinary and multi-instrument analyses that utilize the unique complementary value of G/G-FO mass-change observations in combination with other remote sensing data (e.g., satellite altimetry or precipitation observations) and *in situ* data (e.g., surface deformation or ocean temperature profiles). Such *hydrogeodetic* combinations yield improved spatial and temporal resolutions that enable advances in Earth system process understanding, which increasingly advance societal applications of science results in support of NASA's programmatic focus on **Earth Science to Action**, which seeks to "advance and integrate Earth science knowledge to empower humanity to create a more resilient world."

Section A: GRACE and GRACE-FO Geodesy

The project status reports presented under the previous heading were part of the first section of the agenda (Session A1) as were two additional sessions: Analysis Techniques and Intercomparisons (Session A2) and NGGM and Bridging the Gap (Session A3), which focused on plans, concepts, and technologies being developed for future gravity missions. Highlights from each of these two sessions follow in the next two subsections.

Analysis Techniques and Inter-comparisons

This session featured 15 presentations by the SDS centers and ST members on progress in instrument data calibrations and novel data processing algorithms and methods, including data-fusion with other observations.

Representatives from G/G-FO processing centers presented updated gravity-field time-series data,[6] which capitalize on improved parameterizations,

[3] Open science refers to the principle and practice of making research products and processes available to all, while respecting diverse cultures, maintaining security and privacy, and fostering collaborations, reproducibility, and equity. To learn more about how this is being implemented in the context of NASA Earth Science see, **Open Source Science: The NASA Earth Science Perspective**, in the September–October 2021 issue of *The Earth Observer* [**Volume 33**, **Issue 5**, pp. 5–9, 11].

[4] Via its **web portal GravIS**, GFZ provides user-friendly mass-change products based on GRACE/GRACE-FO (G/G-FO) tailored for applications in the fields of hydrology, oceanography, and cryosphere.

[5] A ***mascon***, or mass concentration block, is a form of gravity field basis functions to which G/G-FO's inter-satellite ranging observations are fit.

[6] The SDS centers mentioned earlier are a subgroup of this larger group of data processing centers for G/G-FO.

better instrument error characterizations (e.g., from star cameras, accelerometers, or ranging instruments) and background models (e.g., for tides) for improved monthly mass change data and uncertainty quantification. The highly accurate LRI data provides further opportunities to identify and characterize measurement system errors, which can be exploited for G-FO data processing but is also informative in the development of the future GRACE-C mission. However, it was also shown that several metrics used in identifying gravitational errors are sensitive to the estimated satellite trajectory, and consequently a sufficient understanding of the orbital trajectory is necessary to make accurate adjustments to the gravity field based on satellite observations.

The G/G-FO data products make use of ground-based geodetic observations, such as satellite laser-ranging (SLR) to a network of dedicated SLR satellites, which can be used to extend the G/G-FO interannual data record back to ~1994 – albeit at a much-reduced spatial resolution. Additionally, SLR data provide an important validation and performance assessment opportunity for G/G-FO observations. In that regard one presenter showed results indicating the recent G-FO accelerometer updates have indeed resulted in better gravity and mass change fields. Other speakers discussed the value and potential for improvement that could be achieved by combining G-FO and SLR observations more formally to exploit the data strengths of the different observation types in an optimal way. Such approaches could reduce uncertainties in global ocean and land ice mass changes. Furthermore, deployment of stable, long-term ocean bottom pressure (OBP) recorders in the Arctic Ocean in 2022 has enabled progress on G/G-FO OBP data validation. The data from these OBP recorders are entirely independent of G/G-FO observations and are thus very valuable to assess the satellite data record. An initial comparison between 1.5 years of OBP data and various G-FO OBP products suggest excellent agreement.

The data collected from G/G-FO has a native resolution of about 300 km (~186 mi). By jointly analyzing these G/G-FO data with higher-resolution surface elevation changes from a multimission synthesis of radar and laser satellite altimeters, net mass changes can be effectively downscaled (within a *Bayesian framework*) to less than 20 km (~12 mi) resolution, which is sufficiently high resolution to resolve individual ice streams in Antarctica that cannot be separated using G/G-FO data alone.

NGGM and Bridging the Gap

The presenters in this session provided status-update on the GRACE-C mission, a joint project between NASA and the Deutsches Zentrum für Luft- und Raumfahrt (DLR) [German Aerospace Center], as well as on future instrument developments and mission concepts.

The **2017 NASA Earth Science Decadal Survey Report** highlighted mass-transport monitoring through gravity change as one of five *designated observables* (i.e., top priorities for study) in Earth observations for the next decade in collaboration with international partners. The GRACE-C project successfully passed the NASA/JPL Mission Concept Review in June 2022, and the NASA Key Decision Point B review in September 2023 and is currently in its Phase B project definition phase. GRACE-C will be a single satellite pair based on a fully redundant LRI (as demonstrated on GRACE-FO) in a polar orbit at 500 km (~311 mi) altitude. To avoid a data gap after GFO, a launch date of no later than 2028 is targeted for GRACE-C.

Similarly, GFZ has been conducting model simulation studies to determine the value of adding a second satellite pair, dubbed Next-Generation Gravity Mission (NGGM) in Europe. The experiments reveal that advanced parameterization techniques for improved de-aliasing of short-term mass variations can significantly reduce data errors and open the possibility for higher spatial and temporal resolution data products and science applications.

The technology demonstration LRI on G-FO has surpassed its performance requirements. With a LRI expected to be the primary instrument for the GRACE-C mission as well as other future GRACE-like missions, development of a new technique is required to provide long-term laser frequency knowledge to provide a scale correction factor to the geodesy measurement. The LRI-team presented updated results of a so-called *scale factor* measurement technique that allows the accurate determination of the laser frequency on-orbit that can meet the stringent GRACE-C mission requirements. This was achieved with a dual frequency modulation scheme, and a prototype electronics unit has been developed and tested, demonstrating performance better than the expected mission requirements.

There were also reports on progress in technology development of low-frequency optomechanical accelerometers for geodetic applications. These highly-sensitive, compact, portable – and cost-effective – optomechanical inertial sensors build upon recent advances in optomechanics to measure accelerations with small form factors. The development of a sensor with lower cost, size, weight, and power – yet with GRACE-like performance – is a major achievement as these could be integrated into cost-effective mission designs, spacecraft miniaturization, simplified architectures, as well as for the deployment of constellations of satellite pairs flying at lower altitudes.

Section B: Geophysics and Climate Science

There were five sessions included in this section of the agenda, which are summarized in the subsections below as follows: Hydrology (Session B4), Cryosphere

(Session B2), Solid Earth Sciences (Session B1), Oceanography (Session B3), and Multidisciplinary Science (Session B5).

Hydrology

This session, with 12 presentations, highlighted advances in hydrology research and applications using G/G-FO data enabled by the unique value of long, uninterrupted mass change climate data record.

The topic of terrestrial water storage variations in California came up in several presentations, focusing on the see-saw swings between very wet and very dry years and the early impacts on groundwater recharge after the record-breaking snow accumulation during the 2022/2023 winter. The process of groundwater recharge – an important objective in the 2017 Earth Science Decadal Survey – is not well understood because of the challenges in observing infiltration of new water supply into the ground and the effects of rate of input, amount of input, and various aquifer characteristics. By combining observations of precipitation, snow water equivalent, surface water storage, ground surface deformation, and groundwater storage from G/G-FO, recharge behavior can be characterized in a natural experiment where source inputs are effectively not limited, but recharge capacity is limited. Results of studies shown during the meeting reveal that only a fraction of total available potential recharge can enter the aquifer, and that G/G-FO observations allow us to measure the effective aggregated recharge capacity and how it varies with several predictors. Another paper reported that subsurface water increases in California's Sierra Nevada by 0.6 m (~2 ft) from October 2022 to June 2023, which represents 43% of the cumulative precipitation.

Several presenters reported on efforts to advance concepts to downscale G/G-FO data to bring the information closer to decision-making scales and expand water-related applications, as well as to fill gaps and expand the data record with multisensor observations. One presenter described a new spectral approach that employs wavelet multiresolution analysis to combine seasonal terrestrial water storage change data from G/G-FO with those from global navigation satellite system (GNSS)[7] **ground station networks** to downscale the observations to smaller hydrological basins and to better separate processes over complex topographical terrain. This method can also be used by fusing G/G-FO and hydrological model data [e.g., from NASA's **Global Land Data Assimilation System** (GLDAS) models at continental scales]. Importantly, the method yields trends and long-term signals that match G/G-FO observations – a strength of the observing system. Another approach used a statistical Bayesian framework to incorporate G/G-FO observations and Soil Moisture Change data from different available sources [e.g., NASA's **Soil Moisture Active Passive** (SMAP) mission] to obtain nonparametric likelihood functions that allow for downscaling. A statistical technique called *cyclostationary empirical orthogonal function (CSEOF)* analysis – which is used to interpret space-time variability in a large dataset – allowed researchers to fill short data gaps (~1 year) in G/G-FO record (e.g., between 2017 and 2018 – the gap between GRACE and GRACE–FO) without having any additional data. With the support of physically-related data (e.g., precipitation and temperature), CSEOFs can be used to reconstruct water changes into the past or fill larger data gaps. Such datasets improve understanding of trends and natural variability and anticipate future trends in response to climatic changes.

Another presenter described a science study that found an apparent abrupt decline in temperate (non-ice) Terrestrial Water Storage (TWS) in 2015 to a new, lower regime that appears to be unique in the past 33 years. The triggering event for this new lower TWS regime appears to be the massive drought in Brazil in 2015. Subsequent droughts around the world (e.g., Europe, the western U.S., Canada, central Africa, and southern Brazil) have helped to keep TWS values depressed. Warm global sea surface temperatures, prevalent since 2015, have decreased rain accumulation over the continents, reducing TWS.

In the European Alps region, a G/G-FO data analysis found that glacier and ice changes are the major contributors to the observed signals. Overall, glaciers here have lost ice mass at rates between 1.4 to 2.2 Gt/year since 2002. Advances in spatial downscaling and data combinations are expected to allow for improved estimates and applications, including geological hazard monitoring.

In Northern Italy, accelerated groundwater loss has been detected using G/G-FO, well measurements, and vertical land motion observations. Since 2015, the groundwater loss has accelerated. Assuming a best-case scenario (conditions similar to 2007–2014), it could take 13–28 years for ground water storage to recover from recent long-term period of decline, thus setting the stage for prolonged drought conditions.

Since a pioneering study in 2014, it is well-established that G/G-FO observations of TWS are an effective means to estimate flood potential and flood risks due to water-saturated soil. Novel G/G-FO data processing schemes that exploit sub-monthly variations of total water storage enabled researchers to delineate basin-specific storage-discharge dynamics more accurately. They found that at submonthly timescales in many global basins, water storage (i.e., saturated soil) has

[7] GNSS is a broad term encompassing different types of satellite-based positioning, navigation, and timing (PNT) systems used globally. The U.S. Global Positioning System (GPS) is one such type of Global Navigation Satellite System. There are various GNSS networks. The focus in this context is on the GPS stations in the US.

more impact on whether a flood will occur than the amount of precipitation that falls.

Along the Nile River, G/G-FO data were used to monitor water changes in crucial artificial reservoirs. These data indicate that water losses through underground-seepage over the geologically highly fractured region via a complex network of shear systems, faults, and fractures, are significant and could impact the delicate water balance in the region. A separate study focusing on nearby Southern Arabia found that intense tropical cyclones (wind speeds > 64 kph or ~40 mph) have doubled in the past decade compared to the preceding two, which resulted in significant recharge of the aquifers in the study area. The findings demonstrate the ability of G/G-FO to capture recharge signals and monitor aquifer systems in poorly gauged basins and highlight the significant role of tropical cyclones in recharging aquifers in arid Arabia.

Cryosphere

The five contributions in this session reported on new ice mass balance results of the Earth's land-ice, as well as on novel data-combinations approaches that can improve the spatial resolution over G/G-FO-only data.

The Antarctica Ice Sheet contributes to the largest sea level rise potential and remains as the largest uncertainty source in the prediction of future sea levels. Data from G-FO and the **Ice, Clouds and land Elevation Satellite–2** (ICESat-2) mission have been used to track ice sheet mass and height changes in Greenland and Antarctica, respectively. By combining the strengths of G-FO (gravity or mass change) and ICESat-2, (laser altimetry) data, a more accurate and less uncertain estimate of ice sheet mass changes can be achieved. This combination has led to a proposal for an enhanced iterative algorithm for deriving Antarctic mass balance, incorporating key technologies such as altimetry, gravity measurements, Global Positioning System (GPS) satellite data, and surface mass balance models. The study utilizes an effective density map derived from ICESat-2 and tests the algorithm's sensitivity and uncertainty with synthetic data, considering realistic physical processes and variability. This approach aims to address discrepancies in estimating ice mass loss in East Antarctica and provides important guidance for optimizing future ground measurements (i.e., GPS station positions). Another presentation focused on understanding the differences in mass change recovered by the G/G-FO and IceSat-2 missions – both in terms of spatial distributions and total magnitudes – to ultimately determine a best combined estimate of ice sheet mass change leveraging the strengths of each mission.

Temporal gravity field estimates from G/G-FO data reveal that the Antarctic ice sheet contributed approximately 6.1 mm (~0.2 in) to global sea level rise from 2002–2022, with a net loss of ~2150 GT of mass. While mass change accelerated during the GRACE era, it has decelerated during the GRACE-FO era – due to increased mass gain in East Antarctica. The deceleration is attributed to surface mass balance processes: annual precipitation and increased incidences of extreme weather events in East Antarctica, challenging predictions based on correlations with climate indices like Southern Annular Mode and El Niño Southern Oscillation.

A related study confirmed a pause in Antarctica's mass loss, a non-accelerating mass loss in Greenland, and a steady loss from glaciers and ice caps away from the poles. The use of the LRI observations enabled novel submonthly analysis in key regions (including the Amundsen Sea Embayment of West Antarctica and the Pine Island/Thwaites basins) to gain more understanding of fast ice dynamics and their spatial extent.

While G/G-FO data span two decades, estimates of Earth's oblateness from other satellite observations that date back to 1976 and provide a much longer data record – albeit at much coarser spatial resolution. This half-century long timeseries provides important constraints on ice mass change prior to the launch of GRACE in 2002. The data suggest that ice mass loss had already begun to accelerate by the 1990s. Recent progress in Earth system models, in conjunction with the long satellite data record, are being used to isolate trends in *glacial isostatic adjustment* (GIA) – which is the vertical movement of the Earth's surface after the weight of glaciers is removed from them – and to improved estimates of ice mass loss prior to GRACE.

Solid Earth Sciences

Two presenters in this session described their efforts to evaluate signals in the G/G-FO data record associated with earthquakes. The G/G-FO data provide a unique opportunity to observe the Earth's response to great earthquakes across diverse tectonic settings at time scales from days to decades. Using 13 earthquakes of magnitude (Mw)>8.0 over the last 20 years, it was found that elastic bulk modulus and viscosity govern large-scale coseismic and postseismic gravimetric changes, respectively. By constraining the solid Earth's viscosity structure, improved physics-based models of long-term postseismic changes can be developed that incorporate observations from G/G-FO. The portion of the long-term gravity change signal that can be attributed to these earthquakes can then be removed from the G/G-FO data to better quantify processes related to ocean mass and hydrology changes. When physics-based models are not available, alternative statistic-based approaches can be used to remove the co- and post-seismic signature of large earthquakes (e.g., 2004 Andaman-Sumatra and 2011 Tohoku, Japan quakes) from the G/G-FO data.

As the G/G-FO data record extends into its third decade, the long time series of Earth gravity changes requires careful consideration of the solid-Earth response to contemporary surface mass changes. To isolate the gravity signature of any surface mass signal, it is becoming evident that simple elastic loading corrections are no longer sufficient. Recent advances in mantle *rheology* – describing and understanding the nature of Earth's mantle – derived in mineral laboratory experiments, tidal modeling, and seismic imaging provide unequivocal evidence of anelastic contributions to solid-Earth deformation on time-scales ranging from hours to decades. New developments in the solid-Earth capabilities of JPL's **Ice-sheet and Sea-level System Model** (ISSM) in the form of viscoelastic solvers for Love numbers and sea-level change was used to implement and explore the so-called Extended Burgers Material (EBM) and so resulting viscoelastic deformations between the seismic and GIA time scales. Preliminary testing with EBM rheology shows potential for a ~15–20% increase in mass change trends for some regions.

A subdecadal variation of large-scale (i.e., spanning over continental scales) gravity signals with a period of approximately six years has attracted intense interest in the geodesy and geodynamic communities. Earth's fluid core motions, magnetic field, Earth rotation, and crustal deformations have been invoked as causes for this signal. An analysis of G/G-FO data showed that a significant part of the approximately six-year signals is in fact due to climate-related oscillation of ocean-atmosphere coupling in the Pacific and Atlantic and variations in the land water storage over Africa.

Oceanography

In the oceanography session, five presenters reported on the combination of G/G-FO, satellite altimeters (e.g., from the joint NASA–European **Sentinel-6 Michael Freilich** mission), and *in situ* ocean floats (e.g., **Argo**) to investigate variations in sea level and ocean circulations – e.g., see **Figure 1**. Other presenters discussed improvements in data processing by reducing errors in atmospheric tides that could lead to spurious trends or double-counting a subset of ocean tides and by incorporating new dedicated ocean data grids that remove geodetic signals not related to ocean dynamics (e.g., global ocean mass; large earthquake signals).

Another presenter described how ocean mass redistribution and regional sea-level rise in the North-West Pacific marginal seas (i.e., around Japan and north of the Philippines) is impacted by seafloor deformation from earthquakes, which alter the ocean bathymetry. G/G-FO data are key to isolating these deformation effects, which in turn allows better sea level projections that can be used for planning purposes.

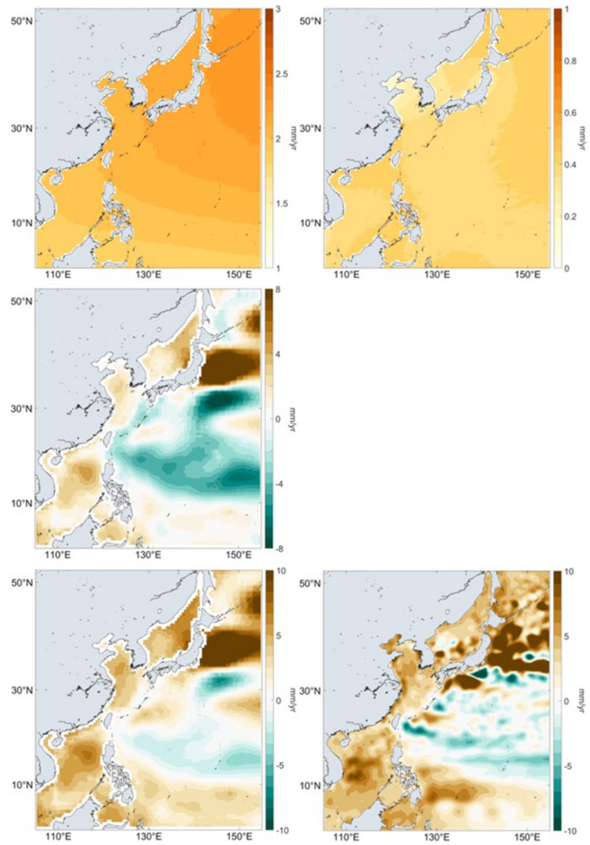

Figure 1. The fist two rows of maps show estimates of individual components of the observed sea level trend in the northwestern Pacific from 2003 to 2016 including contributions from: land ice melt [*top row, left*], non-ice land water storage [*top row, right*], and stereodynamic effects [middle row], which are estimated by directly combining *in situ*-based steric sea level (i.e., based on Argo ocean profiling floats) with the GRACE-derived ocean mass changes. The bottom row shows the sum of all of the components of sea level trend on the top two rows [*bottom row, left*], compared the same measurement using satellite-altimetry [*bottom row, right*]. These data clearly show the strong earthquake-related signature of ocean mass change east of Japan. **Image credit:** Felix Landerer/updated from a similar figure published in ***Nature's Communications Earth & Environment***.

While long-term sea level trends are of major concern, the seasonal cycle is the dominating climate signal in ocean bottom pressure variability. Accurate representation of seasonal cycle is thus key to efforts to improve observations and models of ocean bottom pressure. Examining differences between models and observations elucidates remaining uncertainty in observations and missing physics in the models (e.g., lack of intrinsic variability due to coarse resolution, no accounting of gravitational and loading effects). This allows researchers to advance the quality of ocean mass change observations and unravel underlying dynamics.

Lastly, ocean bottom pressure observations from G/G-FO have been used to monitor transport variability of deep currents associated overturning circulation in the Northern Hemisphere (the Labrador Current) and Southern Hemisphere (Weddell Sea Bottom Water). This deepwater transport provides an important

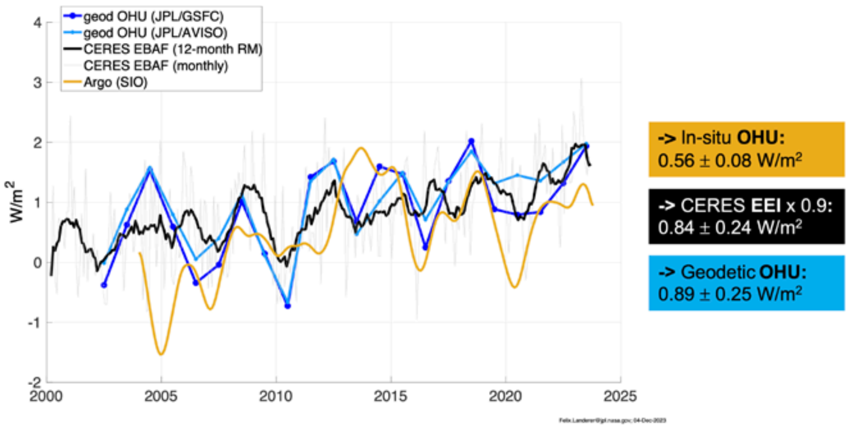

Figure 2. This graph shows different estimates of ocean heat uptake (OHU), measured with *in-situ* ocean floats (orange curve), from top-of-the-atmosphere radiance satellite measurements of Earth energy imbalance (EEi) (black curve), and from geodetic satellites, i.e., G/G-FO and altimeters (blue curve). The satellite measurements agree well and show an increasing energy imbalance over the last 20 years. **Image credit:** Felix Landerer/originally in ***Geophysical Research Letters.***

pathway for the sequestration of excess atmospheric heat and carbon from locations of water mass formation. Continuous observations of deep ocean currents provide valuable insight into Earth's climate system. However, harsh conditions and complex recirculation transport pathways make *in-situ* observations of these deep flowing currents challenging.

Interdisciplinary Science

Six presenters contributed to this session. The first study revisited geodetic assumptions about measuring so-called Earth Center-of-Mass (CM) motions that can be traced to planetary-scale seasonal and long-term variations of water cycling between the land the oceans. Differences in SLR and G/G-FO estimates of CM estimates can be helpful to refining global circulation models. In a related study, G/G-FO and SLR data have been used to pin down the causes and origin of polar motion, particularly the mass component related to gravity changes. A novel hybrid SLR/GRACE time-variable gravity approach closely aligned well with the hydrological excitation in independently polar motion.

Errors in GIA corrections impact altimeter estimates of sea level and ocean mass estimates and the so-called *sea level budget*. Choices in modeling GIA, particularly based on paleoshoreline sites, affect Earth's viscosity structure and GIA response, influencing global mean sea level (GMSL) budget closure. Even minor Earth model changes can have notable effects on the alignment of GMSL (altimetry), ocean mass (GRACE), and steric sea level change (Argo). Thus, future research needs to focus on accounting for the complex three-dimensional structure of the solid Earth to improve GIA corrections and more accurately isolate contemporary mass change in the G/G-FO data record.

Despite GIA uncertainties, G/G-FO, in combination with sea level measurements from altimetry, provide a unique capability to measure changes in ocean heat content. The ocean takes up nearly 90% of Earth's current energy imbalance, signifying their important role in overall planetary heating. Two presenters reported consistent findings of ocean heat uptake rates of 0.9 W/m^2 based on the indirect geodetic satellite measurements of sea level and ocean mass – a value that is entirely independent of other techniques and thus provides crucial validation – see **Figure 2**. In addition, the results indicated the overall heating rate over the last decade has increased, which means heat accumulation is accelerating.

Summary

The hybrid 2023 G-FO STM brought together over 120 international participants and showcased a broad range of science results and applications that are supported and uniquely enabled by the satellite gravimetry-based mass change observations. The G-FO data now span nearly six years and continue to provide crucial insights into how Earth's hydrosphere, including sea level, ocean currents, and water distribution over land, is changing. The G/G-FO data are extending important climate data records (e.g., the Greenland and Antarctic ice mass time-series, ocean mass sea level data, and TWS over land) into their third decade. The upcoming GRACE-C mission will build on and expand this mature data record, which is increasingly enabling important applications in support of water-related decision making and planning.

The G-FO project team remains focused on providing the mass-change data record at a level of performance consistent with that of GRACE. As the current Solar Cycle 25 increases towards its anticipated maximum in 2024, the team continues to improve the mission's accelerometer data products in support of that goal. Corresponding data improvements in the monthly gravity and mass change products will be released early 2024.

The next G-FO STM will be held from October 8–10, 2024 in Potsdam, Germany, organized by GFZ. Check the **GRACE website** for specific details as the date gets closer. ■

NASA Collaborates in an International Air Quality Study

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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 edited for the context of *The Earth Observer*.

NASA and international researchers are studying the air quality in Asia as part of a global effort to better understand the air we breathe. In collaboration with South Korea's National Institute of Environmental Research (NIER), the **Airborne and Satellite Investigation of Asian Air Quality**, or ASIA-AQ mission, will collect detailed atmospheric data over several locations in Asia in early 2024.

Utilizing aircraft, satellites, and ground-based instruments, the ASIA-AQ team will gather and share data with air quality and government agencies to be used for air quality research and understanding worldwide.

"Our purpose is to improve the understanding of the factors that control air quality," said **Jim Crawford** [NASA's Langley Research Center (LaRC)—*Principal Investigator, ASIA-AQ*]. "Multi-perspective observations are needed because satellites, ground-sites, and aircraft each see different aspects of air quality that need to be connected."

While satellite views and ground measurements provide significant data, alone they cannot completely illustrate air quality problems and the sources that cause them. By adding airborne measurements to models along with satellite and ground-based observations, scientists can achieve a multidimensional, detailed perspective that evaluates our air quality models from all angles.

A pair of NASA science aircraft will help provide those additional dimensions to air quality observations. The DC-8 from NASA's Armstrong Flight Research Center (AFRC) – see **Photo** – is outfitted with 26 instruments and will fly at low-altitudes to collect data from the atmosphere closest to the ground where people and habitats are impacted.

Meanwhile, the G-III from LaRC (in Hampton, VA), will fly at 28,000 ft (~8.5 km) altitude to create a high-resolution map of the pollution distribution in each study area, and how it changes throughout the day. Together with Korean aircraft from NIER, the NASA planes and instruments will supplement and cross-reference the observations made from the ground and satellite instruments.

"Science missions for air quality [like ASIA-AQ] take a holistic approach of multiple perspectives to better understand our pollution issues," said **Laura Judd** [LaRC—*Platform Scientist, G-III aircraft*]. "If we can better understand how models simulate our air pollution, then we can forecast when these events [will] unfold, and be able to disseminate that information to the public to make informed decisions."

Photo. NASA's DC-8 aircraft takes off from NASA's Armstrong Flight Research Center (in Palmdale, CA) to conduct test flights as part of the Airborne and Satellite Investigation of Asian Air Quality, or ASIA-AQ, mission that will collect detailed air quality data over several locations in Asia. **Photo credit:** Carla Thomas/NASA

Pollution changes as populations shift, economies ebb and flow, and industries move or evolve. The ASIA-AQ project will improve our ability to measure those changes and how they connect to the global scale. Bringing scientists, aircraft, and instruments together from across Asia and around the world, ASIA-AQ demonstrates how scientific advancement is a collaborative effort.

"Scientists and agencies in each of the participating countries will ensure that ASIA-AQ targets the most important open air quality questions in their specific region," said **Barry Lefer** [NASA Headquarters—*Program Scientist for Air Quality Research*]. "And they'll be the ones to implement improvements in their forecast models and advocate for policy changes." ASIA-AQ is a joint effort between NASA, NIER, and several international organizations including the Department of Environment and Natural Resources (DENR) of the Philippines, the Universiti Kebangsaan Malaysia (UKM), the Geo-Informatics and Space Technology Development Agency (GISTDA) of Thailand, and the Ministry of Environment (MOENV) of Taiwan. ■

OpenET Study Helps Water Managers and Farmers Put NASA Data to Work

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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 edited for the context of *The Earth Observer*.

As the world looks for sustainable solutions, a system tapping into NASA satellite data for water management has passed a critical test. Called **OpenET**, the system uses an ensemble of six satellite-driven models that harness publicly available data from the Landsat program to calculate *evapotranspiration* (ET) – the movement of water vapor from soil and plant leaves into the atmosphere. OpenET does this on a field-level scale that is greatly improving the way farmers, ranchers, and water resource managers steward one of Earth's most precious resources.

Researchers have now conducted a large-scale analysis of how well OpenET is tracking evapotranspiration over crops and natural landscapes. The team compared OpenET data with measurements from 152 sites with ground-based instruments across the U.S. In agricultural areas, OpenET calculated evapotranspiration with high accuracy, especially for annual crops such as wheat, corn, soy, and rice. The researchers reported their findings on January 15, 2024, in ***Nature Water***.

"I was pleasantly surprised by the results," said **John Volk** [Desert Research Institute—*Assistant Research Scientist*], the study's lead author. "The accuracy in croplands was quite strong, particularly in western arid regions, which are important areas for agriculture and have water sustainability challenges."

That's welcome news for regions where OpenET data is already being put to work. In Northern California's Sacramento–San Joaquin Delta, water resource managers are using OpenET to help farmers comply with state rules requiring them to report aspects of their water use – see **Figure 1**.

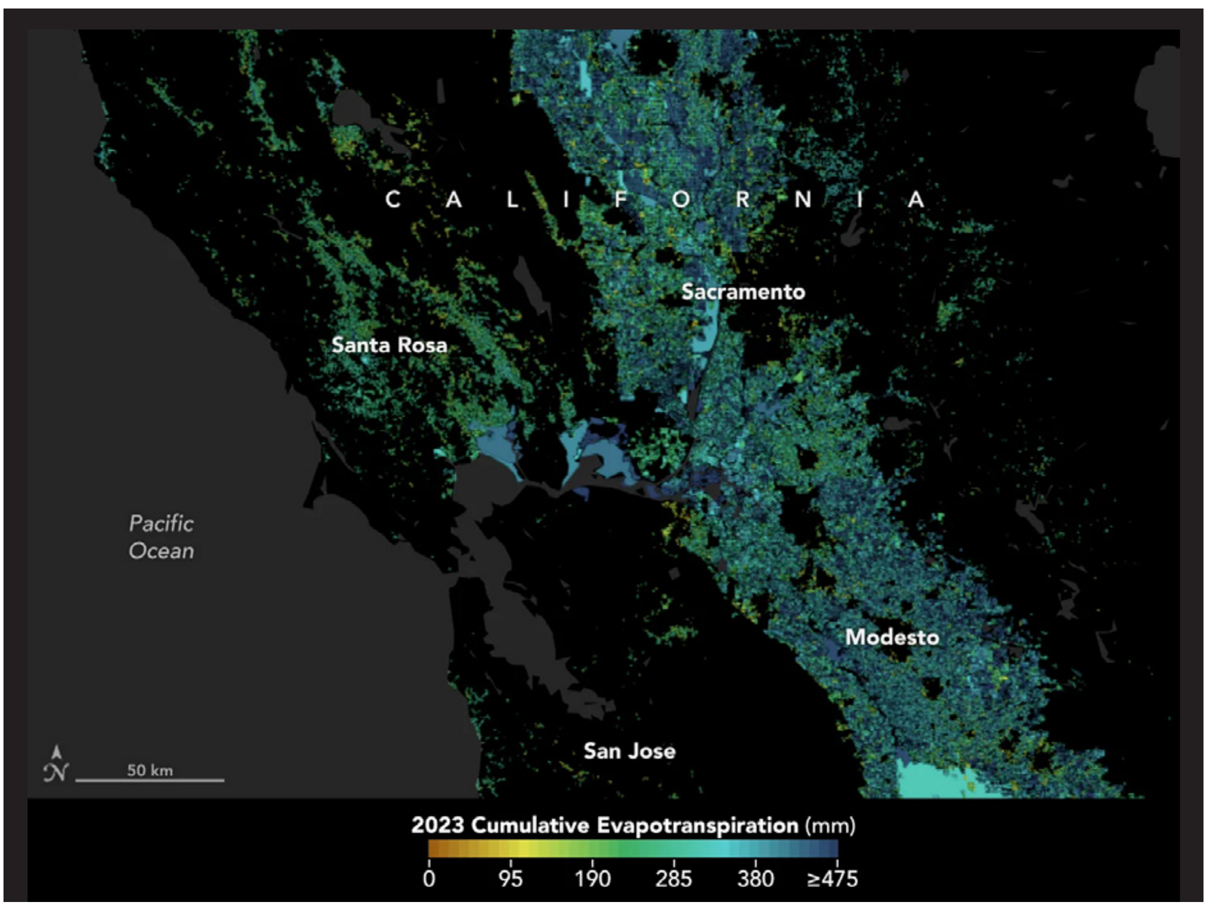

Figure 1. In California, state officials and farmers are using satellite data through OpenET to track evapotranspiration to better manage water resources. The process is a window into the water consumed by plants and crops, such as those grown in the Central Valley. **Figure credit:** NASA Earth Observatory using *openetdata.org*

The new study "gives us more confidence that these numbers are accurate, and that OpenET is continually improving over time," said **Lindsay Kammeier** [California State Water Board—*Senior Engineer*], who was not involved in the new research.

"ET is notoriously difficult to calculate," she added. "Having a really accurate number helps us to make decisions to manage the environment, manage for agricultural uses, and manage for urban uses better and from a common understanding."

"While many people are familiar with what one inch of rainfall means, few stop to think about one inch of evapotranspiration returning to the atmosphere," said **Forrest Melton** [NASA's Ames Research Center—*OpenET Project Scientist*]. "OpenET is working to make the unseen process of evapotranspiration as easy to track as checking the amount of rainfall in the daily weather forecast."

Evapotranspiration is the natural process in which water moves to the atmosphere from the surface. The term combines evaporation – water changing from liquid to gas (vapor) and rising from soil, lakes, and oceans – and transpiration, the "exhaling" by plants as they release moisture back into the air. After precipitation, evapotranspiration is one of the most important factors for estimating how much water is available for crops or other plants.

For farmers and water managers, accurate data provides a measure of the amount of water required through irrigation to replace the water that has been consumed by evapotranspiration. Knowing precisely how much water is available helps people give plants the moisture they need to flourish, without needing to apply too much. And that, in turn, can help save money for water and for the electricity used to pump water for irrigation.

But all that rising water vapor is invisible, making it difficult and expensive to track on the ground.

Farmers, scientists, and others previously relied on estimates of *potential evaporation* based on temperature, humidity, and other weather data. Or they turned to ground-based stations such as flux towers, equipped with sensors that monitor carbon dioxide, water vapor, and the exchange of heat between Earth's surface and the atmosphere – a process crucial to calculating evapotranspiration.

But while they tend to be highly accurate, flux towers are expensive to set up and maintain, so there are a limited number, and their data is local and cannot represent wider regions. That's where calculating evapotranspiration from space comes in. Satellites pass over the same areas regularly, offering consistent monitoring.

The OpenET consortium includes NASA, U.S. Geological Survey (USGS), and the U.S. Department of Agriculture working with Desert Research Institute and nearly a dozen other universities, Environmental Defense Fund, and Google Earth Engine. OpenET's primary observations come from the Landsat 8 and 9 satellites, a partnership between NASA and USGS.

The satellites combine data on land surface temperatures and the greenness of plants, among other things. Cooler land surface temperatures over areas with healthier, denser vegetation, for example, usually indicate higher levels of transpiration. That data is then fed into models to calculate evapotranspiration at high resolution – about a quarter of an acre for each image pixel. The new results show that for agricultural lands, OpenET data for monthly, growing season, and annual timescales had an average error rate of about 10–20%. ■

SWOT Satellite Catches Coastal Flooding During California Storms

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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 edited for the context of *The Earth Observer*.

A series of atmospheric rivers drenched California in February, with record amounts of rainfall and hurricane-force winds sweeping across parts of the state. At one point, weather agencies posted flood watches for nearly the entirety of California's coast. The **Surface Water and Ocean Topography** (SWOT) mission captured data on some of the flooding near the community of Manchester, roughly 105 mi (169 km) north of San Francisco – see **Figure**. The satellite is a collaboration between NASA and the Centre National d'Études Spatiales (CNES) [French Space Agency].

Some coastal areas were flooded by both ocean tides and heavy rain, while others were likely flooded only by precipitation. Each pixel in the image represents an area that is 330 x 330 ft (100 x 100 m).

Since December 2022, SWOT has been measuring the **height of nearly all water** on Earth's surface, developing one of the most detailed, comprehensive views yet of the planet's oceans and freshwater lakes and rivers. Not only can the satellite detect the extent of the water on Earth's surface, as other satellites can, but SWOT can also provide water level data. Combined with other types of information, SWOT measurements can yield water depth data in features like lakes and rivers.

"SWOT gives us information about flooding that we've never had before," said **Ben Hamlington** [NASA/Jet Propulsion Laboratory (JPL)—*Lead Researcher, Sea Level Change Team*]. Satellites can provide pictures showing how much of an area is flooded, but unless instruments are already installed on a river or at the coast, it's difficult to know how conditions evolve during and after a flood. "Data from the SWOT satellite, combined with other information, is filling in this picture," said Hamlington.

The SWOT science team made the measurements using the **K_a-band Radar Interferometer** (KaRIn) instrument. With two antennas spread 33 ft (10 m) apart on a boom, KaRIn produces a pair of data swaths as it circles the globe, bouncing radar pulses off water surfaces to collect surface-height measurements. ■

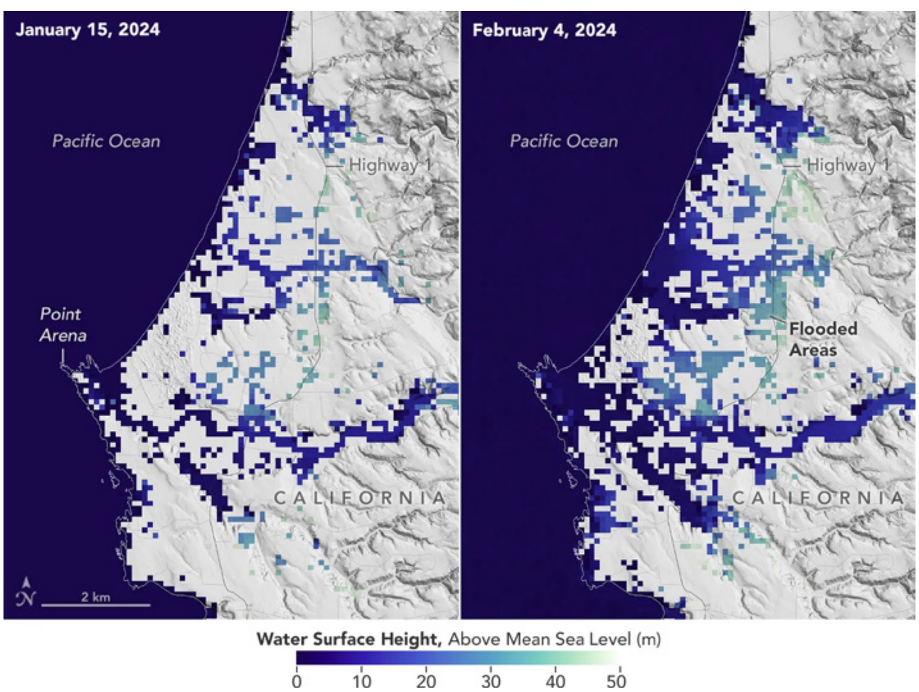

Figure. This image shows SWOT satellite data for water surface height in part of Mendocino County, Northern California, on January 15, 2024, before several atmospheric rivers arrived [*left*], and on February 4, 2024, after the first storms [*right*]. Light blue and green indicate the highest water levels relative to mean sea level. (Inland water heights include the underlying ground elevation.) **Figure credit:** NASA/Jet Propulsion Laboratory (JPL)

NASA Earth Science in the News

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

New assessment of OpenET accuracy points to expanding, vital role of satellite-based water management tools, January 23, 2024, *edf.org*. The satellite-based water data platform **OpenET** demonstrates considerable accuracy in measuring evapotranspiration in agricultural settings according to a new study in ***Nature Water***. *Evapotranspiration* – the amount of water lost to the atmosphere through soil evaporation and plant transpiration – is a key measure of water consumption in agriculture and has previously been difficult and expensive to monitor accurately at scale. A public–private collaboration led by NASA, California State University Monterey Bay, Environmental Defense Fund, Desert Research Institute, and HabitatSeven, OpenET uses publicly available data produced by NASA and United States Geological Survey (USGS) Landsat and other satellite and ground-based systems to calculate evapotranspiration rates at the field level.

"It's truly rewarding to see decades of careful research and hard work by this science community come together, and this study sets a new benchmark for satellite mapping of field-scale evapotranspiration with Landsat," said **Forrest Melton** [NASA's Ames Research Center—*Senior Research Scientist*]. "By documenting the accuracy of the OpenET data, I anticipate that this study will further accelerate the already rapid uptake and use of these data to help solve pressing water management challenges and open up new applications and areas of future study." The study shows OpenET's results are particularly reliable for arid regions like California and the Southwest and for annual crops like wheat, corn, soy, and rice – see **Figure 1**.

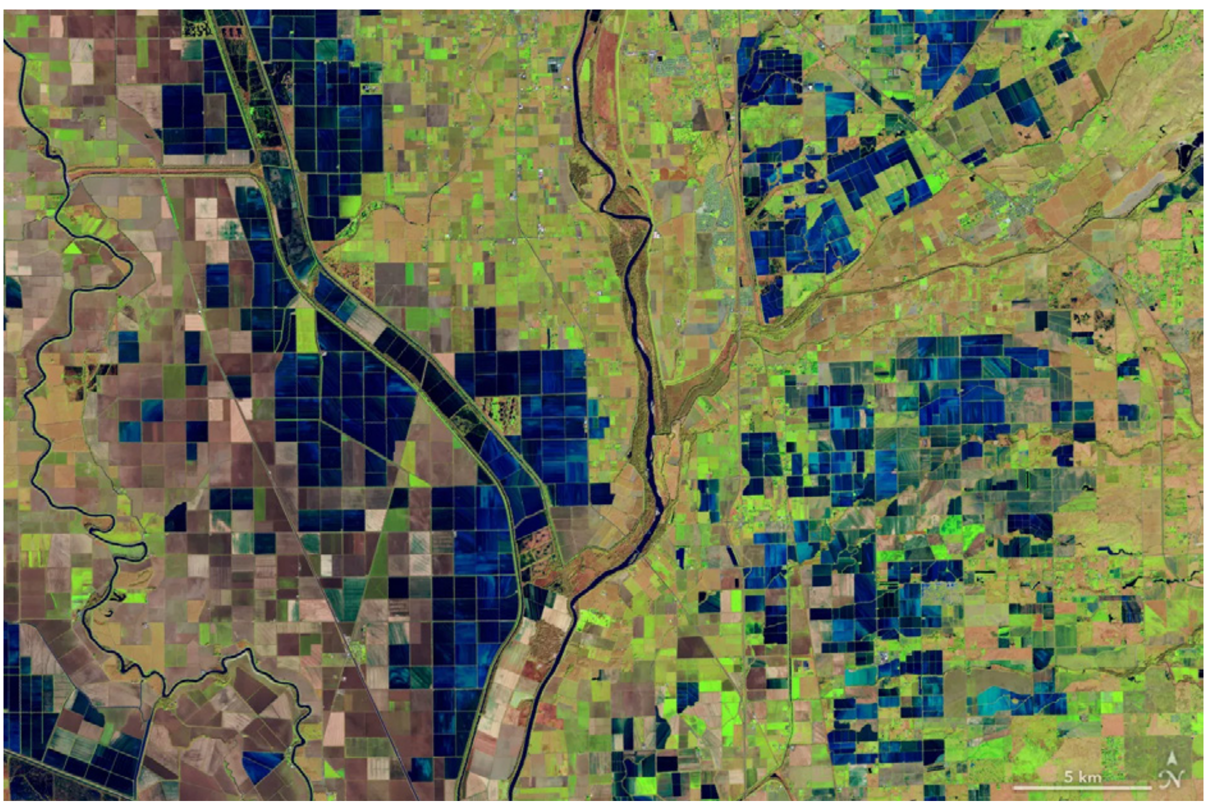


Figure 1. This false-color image, acquired December 26, 2018, with the Operational Land Imager (OLI) on Landsat 8 shows flooded rice fields along the Sacramento and Feather Rivers. Inundated fields appear dark blue; vegetation is bright green. **Figure credit:** Lauren Dauphin/NASA Earth Observatory

NASA Collaborates in an International Air Quality Study, March 1, 2024, *enn.com*. NASA and international researchers are studying the air quality in Asia as part of a global effort to better understand the air we breathe. In collaboration with South Korea's National Institute of Environmental Research (NIER), the Airborne and Satellite Investigation of Asian Air Quality, or ASIA-AQ, mission will collect detailed atmospheric data over several locations in Asia. Utilizing aircraft satellites, and ground-based instruments, the ASIA-AQ team will gather and share data with air quality and government agencies to be used for air quality research and understanding worldwide.

"Our purpose is to improve the understanding of the factors that control air quality," said **Jim Crawford** [NASA's Langley Research Center—*Principal Investigator, ASIA-AQ*]. "Multiperspective observations are needed because satellites, ground-sites, and aircraft each see different aspects of air quality that need to be connected."

While satellite views and ground measurements provide significant data, alone they cannot completely illustrate air quality problems and the sources that cause them. By adding airborne measurements to models along with satellite and ground-based observations, scientists can achieve a multidimensional, detailed perspective that evaluates our air quality models from all angles.

Can volcanoes cause a major cooling? March 5, 2024, *earthsky.org*. New research in the ***Journal of Climate*** suggests that sunlight-blocking particles from a **super-volcano** eruption would not cool surface temperatures on Earth as severely as previously estimated. In the new study, a team from NASA's Goddard Institute for Space Studies (GISS) and Columbia University in New York used advanced computer modeling to simulate super-eruptions like the Toba volcano in Indonesia, which erupted ~74,000 years ago, with a force 1000 times more powerful than the 1980 eruption of Mount St. Helens. The mystery is what happened after that: namely, to what degree that extreme explosion might have cooled global temperatures. When it comes to the most powerful volcanoes, researchers have long speculated how post-eruption global cooling – sometimes called *volcanic winter* – could potentially pose a threat to humanity – see **Figure 2**.

Previous studies agreed that some planet-wide cooling would occur but diverged on how much. Estimates have ranged from 3.6–14 °F (2–8 °C). The researchers found that post-eruption cooling would probably not exceed 2.7 °F (1.5 °C) for even the most powerful blasts. Lead author **Zachary McGraw** [GISS and Columbia University] said "The relatively modest temperature changes we found most compatible with the evidence could explain why no single super-eruption has produced firm evidence of global-scale catastrophe for humans or ecosystems." The most recent super-eruption occurred more than 22,000 years ago in New Zealand. The best-known example

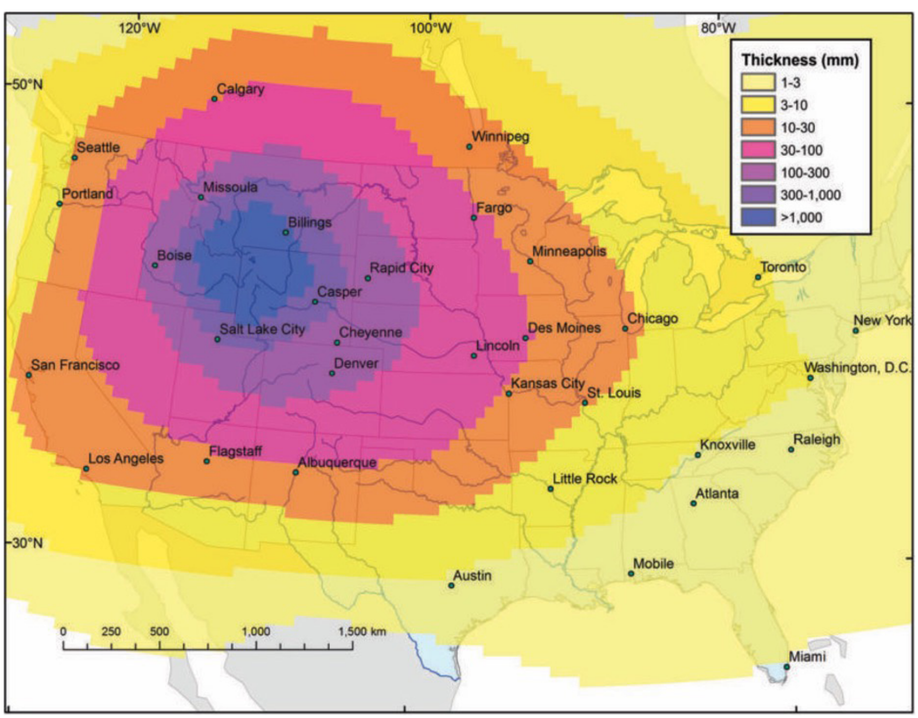
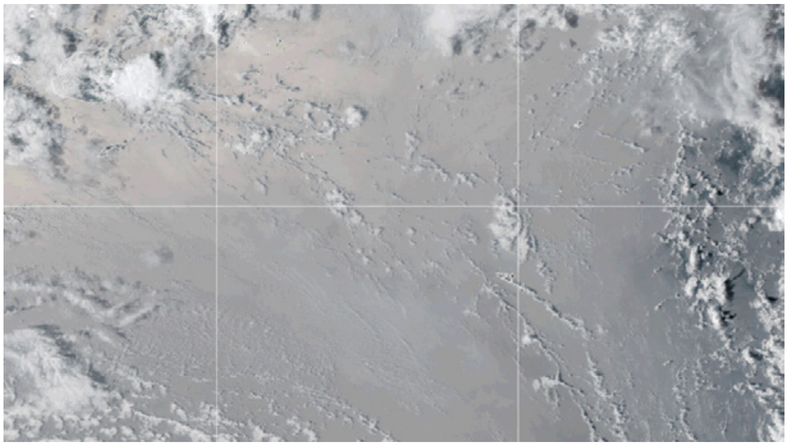


Figure 2. A simulation of possible output of ash from a month-long Yellowstone super-eruption. In the real world, results would vary, depending on wind and eruption conditions. **Figure credit:** USGS



Visualization. The **Advanced Baseline Imager** (ABI) on the **Geostationary Operational Environmental Satellite** (GOES-17) obtained imagery as the powerful eruption of Tonga volcano unfolded on January 15, 2022, that was used to create this visualization. This was the biggest eruption of the twenty-first century – but still fell well short of the criteria needed to be classified as a **supervolcano**, or super-eruption. **Image credit:** NASA/NOAA (via Scitechdaily.com)

may be the eruption that blasted Yellowstone Crater in Wyoming about 2 million years ago. McGraw and colleagues set out to understand what was driving the divergence in model temperature estimates. They settled on a variable that can be difficult to pin down: the size of microscopic sulfur particles injected miles high into the atmosphere. In the stratosphere (~6–30 mi in altitude, or 10–50 km), sulfur dioxide gas from volcanoes undergoes chemical reactions to condense into liquid sulfate particles. These particles can influence surface temperature on Earth in two counteracting ways. They can reflect incoming sunlight (causing cooling) or trap outgoing heat energy (a kind of greenhouse warming effect). The researchers showed to what extent the diameter of the volcanic aerosol particles influenced post-eruption temperatures. The smaller and denser the particles, the greater their ability to block sunlight. But estimating the size of particles is challenging. That's because previous super-eruptions have not left reliable physical evidence. In the atmosphere, the size of the particles changes as they coagulate and condense. Even when particles fall back to Earth and become preserved in ice cores, they don't leave a clear-cut physical record because of mixing and compaction. By simulating super-eruptions over a range of particle sizes, the researchers found that super-eruptions may be incapable of altering global temperatures dramatically more than the largest eruptions of modern times – see **Visualization**. ■

Update from the Executive Editor on the Continued Evolution of *The Earth Observer*

The Earth Observer ended its long run as a NASA print publication at the end of 2022. At that time, the newsletter's production team committed to a transition period during which we would continue to publish bimonthly issues of the newsletter as we planned for "the next step" in the process—which lasted through the end of 2023. The goal had been to be producing content via the new content management system by January 2024. However, as inevitably happens during development, there have been some delays. While the rollout of the new system is now imminent (NET June 2024), we acknowledge there has been an information gap. In an effort to fill it, the team has produced the issue you are reading [**Volume 35**, **Issue 7**] using the traditional pdf format.

Again, on behalf of the production team, I want to thank our readers for their continued patience and adaptability during this time of transition for *The Earth Observer* and extend my heartfelt gratitude to all of you for sticking with us on this journey. We're confident the new online version of our newsletter will be worth the wait.

—**Alan Ward** [Executive Editor, *The Earth Observer*]

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