Over Thirty Years Reporting on NASA's Earth Science Program

The Earth Observer

National Aeronautics and Space Administration

January–February 2023. Volume 35, Issue 1

The Editor's Corner

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A Message from the Executive Editor: Welcome to **Volume 35** of *The Earth Observer* newsletter! After a nearly 34-year run as a NASA print publication, this issue of the newsletter is the first to be published exclusively as a full-color, searchable PDF file on the EOSPSO web site. For the short-term, the plan is to maintain the bimonthly pdf publication format. However, "The Editor's Corner" of this issue offers a preview of some style and formatting changes that will be fully implemented beginning with the March–April 2023 issue. We plan other changes in due time to take better advantage of an online format. We hope the adjustment will go smoothly for those of you accustomed to reading the print version. What will not change—as has been the case since the release the very first issue in March 1989—is *The Earth Observer* staff's commitment to maintaining a high-quality publication that will continue to report the latest news from NASA's Earth Science program. Hope you enjoy this issue.
—**Alan Ward**, *Executive Editor*

The Editor's Corner of the November–December 2023 issue of *The Earth Observer* reported on the successful launch of the international Surface Water and Ocean Topography (SWOT) mission on December 16, 2022. After launch, SWOT entered a period of commissioning, calibration, and validation during which engineers assess the performance of the satellite's systems and science instruments in preparation for the commencement of science operations.

SWOT's K_a-band Radar Interferometer (KaRIn) encountered a technical glitch in late January that required the instrument to be shut down briefly. The SWOT team quickly analyzed the situation and developed a plan to restore operations utilizing a backup KaRIn power unit. (The backup unit was chosen to expedite the restoration of operations and to minimize overall risk to the mission.) On March 9, 2023, KaRIn returned to regular commissioning activities with a planned start to science operations in July 2023.

While full-fledged science operations will not begin until summer, SWOT has already offered a glimpse into the new perspectives that the mission will provide. The "first light" ocean images from KaRIn have revealed sea level anomalies in unprecedented detail. For example, **Figure 1** below shows the Gulf Stream as measured by KaRIn compared to the data obtained from a composite of seven existing altimetry missions.

continued on page 2

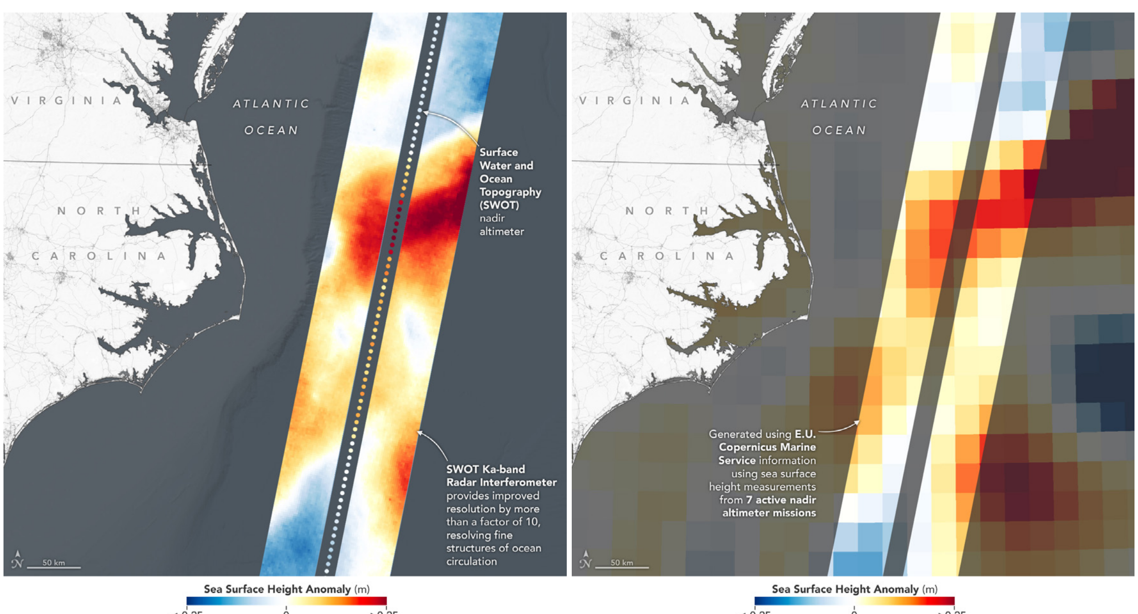

Figure 1. On January 21, 2023, SWOT's KaRIn instrument captured some of its first data over the Gulf Stream in the Atlantic Ocean [*left*]. KaRIn has 10 times the spatial resolution of data taken over the same area by altimeters on seven other satellites, a composite of which is shown for comparison [*right*]. In both images, red represents sea levels higher than the global average, while blue is lower. **Image credit:** [*left*] NASA/JPL; [*right*] NASA/JPL/Copernicus Marine Service of European Space Agency

In This Issue

Even more tantalizing is the first inland imagery obtained over Long Island—see **Figure 2** right—that demonstrates how KaRIn can measure details of smaller lakes, ponds, and rivers—down to as small as 100 m, which far exceeds the capabilities of previous instruments. These new high-resolution data will be used to produce an extraordinary accounting of the freshwater on Earth's surface in ways useful to researchers, policymakers, and water resource managers.[1]

On April 7, 2023, at 12:30 AM EDT a SpaceX Falcon 9 rocket successfully launched from SLC-40 at Cape Canaveral Space Force Station, FL, carrying Intelsat's 40e (IS-40e) commercial communications satellite—which includes NASA's Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission as part of its payload—into geostationary orbit.[2] Once instrument checkout is complete and the mission is operational, TEMPO will be the first space-based instrument to monitor major air pollutants across North America every daylight hour at high spatial resolution. TEMPO will overlap with two other geostationary air quality monitoring instruments, which will form a geostationary air quality (Geo-AQ) constellation. The other two instruments are South Korea's Geostationary Environment Monitoring Spectrometer (GEMS) on the Geostationary–Korea Multi-Purpose Satellite-2 (GEO-KOMPSAT 2B), which is nearly identical to TEMPO, and the European Space Agency's Copernicus Sentinel-4 Ultraviolet Visible Near infrared (UVN) spectrometer, which will embark on upcoming Meteosat Third Generation–Sounder (MTG-S) launches.[3] *The Earth Observer* plans more coverage of TEMPO in its March–April 2023 issue.

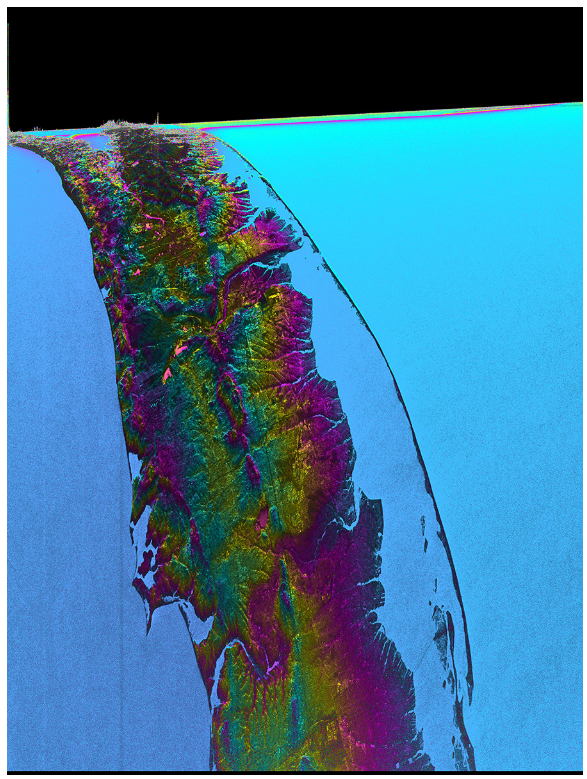

Figure 2. SWOT has greatly enhanced capabilities for monitoring inland bodies of water than previous missions. As an example, this visualization, made using data collected from KaRIn on January 21, 2023, shows water features on New York's Long Island—shown as bright pink splotches. Purple, yellow, green, and dark blue shades represent different land elevations, while the surrounding ocean is a lighter blue. **Image credit:** NASA/JPL

"***The Editor's Corner***" of the last issue also contained a description of two meetings taking place in late 2022, intended to provide an opportunity for the science community to discuss the science and application benefits of continued EOS Flagship observations and the recent Terra orbit lowering maneuver. The first was the virtual *Terra, Aqua, and Aura Drifting Orbits Workshop*, held November 1–2, 2022, that used community input from an earlier Request for Information (RFI); the

[1] To learn more about SWOT—including more details about the "first light" images shown here—see "***Joint NASA, CNES Water-Tracking Satellite Reveals First Stunning Views***".
[2] TEMPO was selected in 2012 as NASA's first Earth Venture Instrument (EVI) mission.
[3] KOMPSAT-2B/GEMS is already in orbit, having launched in February 2020. Sentinel-4A/UVN is expected to launch in 2024 and Sentinel–4B/UVN will follow in 2034.

second was the *Terra Lower Orbit Virtual Community Forum* webinar, held on December 8, 2022. This January–February 2023 issue contains a more detailed summary of these two meetings (see page 18).

My personal thanks to everyone who organized and participated in these two meetings. The strong community engagement, both in terms of the submitted RFI responses and workshop participation, played an important role in all three Flagship missions being invited to take part in the 2023 Earth Science Senior Review, a process that has already begun (mission proposals were due on April 14).

Also, as a follow-on to the *Terra, Aqua, and Aura Drifting Orbits Workshop*, NASA released a ***complementary RFI*** focusing specifically on data continuity for the Flagship mission products. Responses were due April 4, 2023. The RFI seeks to gather input from the community on existing and future data continuity products, gaps and/or alternative data sources, and possible further actions to facilitate transition to the post-Flagship era. See page 22 of the summary article for more details on this RFI. Community input via this RFI will be considered in planning and implementing a follow-on virtual workshop that will be held May 23–25, 2023. Sessions will run daily from 11:00 AM to 4:00 PM EDT.[4]

In other news from NASA's Earth observing fleet, the Total Irradiance Monitor (TIM) and Spectral Irradiance Monitor (SIM) on the Total and Spectral Solar Irradiance Sensor–1 (TSIS-1), mounted on the International Space Station's (ISS) ExPRESS Logistics Carrier-3, continue to provide high quality data despite some excitement due to recent out-gassing episodes from the docked Russian Soyuz capsule on ISS. TSIS-1 is participating in the Senior Review as it is coming up on the end of its five-year prime mission. The TIM and SIM for the follow-on solar irradiance mission, TSIS-2, successfully completed full environmental testing. They are currently undergoing final calibrations prior to delivery. The Pre-Ship Review is scheduled for December 6, 2023, after which the instruments will be ready for spacecraft integration and testing at General Atomics. Launch readiness is scheduled for May 2025.

The 2022 Sun–Climate Symposium took place May 16–20, 2022, in Madison, WI, with a theme of *Improved Climate-Record Reconstructions from Solar Variability and Earth System Observations*. Presenters explored climate reconstructions, how they are developed from direct measurements and proxies, and their role in improving our understanding of climate variability over multiple time scales. The studies covered methods for improving reconstructions, measurements and models of solar and climate variability, long term atmospheric measurements, connections between stellar variability and the Sun, next-generation observations and models, and impacts from improved solar reference spectra. Turn to page 23 to read a summary of the 2022 Sun–Climate Symposium, which includes more detailed reports on the status of TSIS-1 and -2, as well as other present and planned NASA and international Sun–Climate missions.

It was almost five years ago (on May 22, 2018) that the twin satellites of the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission began tracking Earth's water movements and global surface mass changes. Since launch, the mission has delivered 53 monthly global gravity and mass change fields that provide unique insights into variations of ice sheet and glacier mass, groundwater storage, as well as changes in sea level and ocean currents. The combined GRACE and GRACE-FO data record now spans over 21 years.[5] The Global Climate Observing System (GCOS) has recently incorporated terrestrial water storage and groundwater changes as an Essential Climate Variables, recognizing the utility of these measurements from space.

Along with several other missions previously mentioned, the GRACE-FO team is participating in this year's Senior Review cycle to continue the mission beyond its five-year prime mission. By extending GRACE-FO, a near-continuous global data record of mass transport will stretch into its third decade (with GRACE dating back to 2002) and provide important observations of an accelerating water cycle that is increasingly leading to more wet and dry extremes. The long-term dataset on mass change will also provide key observations of trend change in ice mass over Greenland and Antarctica.

In parallel, NASA is working toward launching the Mass Change (MC) mission in 2028. MC is one of five Designated Observables the 2017 Earth Science

[4] For more information on the workshop, consult the following ***FAQ***.

[5] GRACE-FO is so named because it followed the GRACE mission, which ran from 2002–2017.

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

AGU	American Geophysical Union
EOS	Earth Observing System
EOSPSO	Earth Observing System Project Science Office
GRACE	Gravity Recovery and Climate Experiment
ISRO	Indian Space Research Organisation
RFI	Request for Information
SLC	Space Launch Complex

Decadal Survey identified as priorities,[6] and is now a component of NASA's planned ***Earth System Observatory***. MC will continue to provide essential data for monitoring, planning, and decision support on global to regional scales. Turn to page 33 of this issue to read a summary of the 2022 GRACE-FO Science Team Meeting to learn more about recent science discoveries from GRACE-FO, application results, and plans for future missions and technology (e.g., MC).

On the public engagement front, after a year of a rapidly increasing in-person presence at venues around the world, NASA's Science Support Office (SSO) closed out 2022 with its long-standing role of organizing the NASA exhibit at the American Geophysical Union (AGU) Fall Meeting. In addition to the traditional in-person exhibit space, the SSO team unveiled their new virtual exhibit platform, *NASA Science Now*. To read about the AGU fall meeting, and the new virtual exhibit space, turn to page 10 of this issue.

Leveraging the global shift toward hybrid events—which accelerated during the pandemic out of necessity but now is fast becoming the "new normal,"—NASA reached larger scientific and public audiences than ever before. The SSO will continue to represent NASA at a variety of virtual and in-person scientific venues and public events in the coming calendar year, continuing to engage, enrich, and empower audiences with NASA Science in 2023—and beyond. ■

[6] To learn more, see "***Thriving on a Changing Planet: A Decadal Strategy for Earth Observations from Space***".

To learn more, see page 10 of this issue.

NASA Unlocks Secrets of the Universe at the 2022 AGU Fall Meeting

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Introduction

In what is now widely regarded as a new standard for major science conferences around the world, the American Geophysical Union (AGU) held its second *hybrid* Fall Meeting after 2021's event marked the first to offer both in-person and virtual participation.[1] The 2022 AGU Fall Meeting was held December 12–16, 2022, at the McCormick Place Convention Center in Chicago, IL, and online everywhere.

NASA's Science Support Office (SSO)[2] continued its long-standing role of organizing the NASA exhibit at the AGU Fall Meeting. The 50x50-ft (15x15-m) exhibit space—shown in **Photo 1** below—as well as NASA's new virtual event space, *NASA Science Now*, showcased the breadth of innovation and creativity driven by NASA Science activities—see *NASA Science Now: NASA's New Virtual Exhibit Space Debuts at AGU* on page 10.

Photo 1. The NASA Science exhibit space at the 2022 AGU Fall Meeting. **Photo credit:** NASA

The 2022 NASA exhibit theme was "Unlocking the Secrets" and featured a keyhole-shaped doorway that encouraged participants to walk through and explore hands-on demonstrations offered by a variety of NASA subject matter experts. NASA's Hyperwall storytelling platform[3] was also prominently featured in addition to traditional table-style stations where attendees were invited to engage with NASA staff representing various focus areas of NASA's Science Mission Directorate (SMD), including Earth Science, Planetary Science, Heliophysics, Astrophysics, Biological and Physical Sciences, Small Satellites, Space Technology, and Student Opportunities.

[1] To read about the first NASA Science hybrid exhibit at the 2021 AGU Fall Meeting, see "NASA Science at the First Hybrid AGU Fall Meeting" in the January–February 2022 issue of *The Earth Observer* [**Volume 34, Issue 1**, pp. 16–19—***go.nasa.gov/3Tx0wps***].

[2] The SSO is the primary point of contact for NASA's Science Mission Directorate (SMD) for science exhibit outreach and product development.

[3] NASA's Hyperwall is a video wall capable of displaying multiple high-definition data visualizations and/or images simultaneously across an arrangement of screens. To view the full library of Hyperwall visualizations and stories, visit ***svs.gsfc.nasa.gov/hw***.

Continuing another tradition, the SSO worked to coordinate and support the 2022 Annual NASA SMD Strategic Content and Integration Meeting, held at the Chicago Marriott Marquis on December 11—the day before the AGU Fall Meeting began. The meeting allowed NASA employees and contractors who contribute to the agency's communication activities at many different NASA centers to convene, both in-person and online, to forge communication and outreach strategies for the coming year—see *Annual SMD Strategic Content and Integration Meeting* below.

The remainder of this article features several photographs intended to give a sense of the robust range of activities that took place in the NASA Science exhibit at the AGU Fall Meeting, along with some descriptive text. The full collection of photos can be downloaded from ***flickr.com/photos/eospso/albums/72177720304623557***.

Annual SMD Strategic Content and Integration Meeting

The hybrid 2022 Annual SMD Strategic Content and Integration Meeting was held at the Chicago Marriott Marquis, on December 11, 2022. Of the 160 NASA employees and contractors who attended the daylong event, approximately 50 attended virtually. This meeting was an opportunity for those involved in NASA's communications activities to meet together, cultivate outreach communications strategies, and guide workflow for the coming year.

Kristen Erickson [NASA Headquarters (HQ)—*Director of Science Engagement and Partnerships*] provided opening remarks and a welcome message before sharing a recorded message from **Thomas Zurbuchen** [NASA HQ—*Associate Administrator for the Science Mission Directorate*].* The daylong event featured talks on the future trajectory of the agency's communication and engagement strategies, content integration and outreach strategies for 2023, an "Ask Us" panel with NASA SMD Division Directors, an update on the agency's digital media landscape and art direction, and plans for coverage of the April 8, 2024, total solar eclipse, including engagement activities leading up to the event.

In the afternoon, there were breakout sessions for Earth Science, Planetary Science, and Heliophysics, where participants discussed story ideas and communication and engagement strategies.

In one notable addition to the traditional meeting agenda, participants took a break from their communications dialog to watch as NASA's Orion spacecraft for the Artemis I mission splashed down in the Pacific Ocean after a 25.5-day mission around the Moon.

* Zurbuchen has since departed NASA, effective the end of 2022.

Kelly Korreck [NASA HQ—*Eclipse Program Manager*] shared details and plans for coverage of the April 8, 2024, total solar eclipse, including eclipse events planned for 2023 and 2024, and eclipse event viewing safety. **Photo credit:** NASA

Lori Glaze [NASA HQ—*Director of the Planetary Science Division*] spoke during the Planetary Science breakout session. **Photo credit:** NASA

NASA Science Exhibit

The AGU Fall Meeting welcomed approximately 18,000 attendees. Located in the McCormick Place Convention Center's exhibit hall, the NASA Science exhibit offered a variety of opportunities for attendees to engage with NASA representatives, including 67 Hyperwall storytelling presentations, 22 tabletop exhibits and hands-on demonstrations, and an assortment of take-home NASA Science products, both digital, via QR codes, and physical, through printed materials like lenticulars, books, brochures, posters, and puzzles. The air was buzzing with excitement for NASA Science—see **Photos 2–4** on page 6. Similarly, attendees were enthusiastic to collect a copy of the 2023 NASA Science Planning Guide,[4] with 6000 copies distributed throughout the event—see **Photo 5** on page 7.

[4] To download a copy of the 2023 NASA Science Planning Guide (a.k.a, NASA Science Calendar), visit ***go.nasa.gov/3Jtewhh***. The product is available in Spanish at ***go.nasa.gov/3Y6a6ki***.

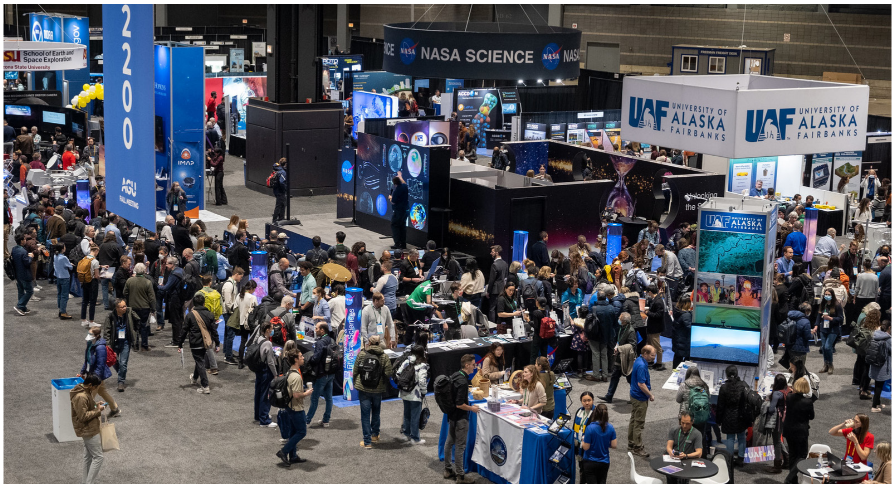

Photo 2. The NASA Science exhibit at the 2022 AGU Fall Meeting featured three main areas—the Hyperwall [*front middle*], *Unlocking the Secrets* demonstration area [*back middle*], and a traditional table area [*spanning left to right*]. **Photo credit:** NASA

Photo 3. [*Right*] **Courtney Lee** [NASA's Goddard Space Flight Center (GSFC)—*Nancy Grace Roman Space Telescope Social Media Lead*] and [*middle*] **Peter Sooy** [GSFC—*Webb Public Outreach Lead*] talked with attendees about the James Webb Space Telescope. **Photo credit:** NASA

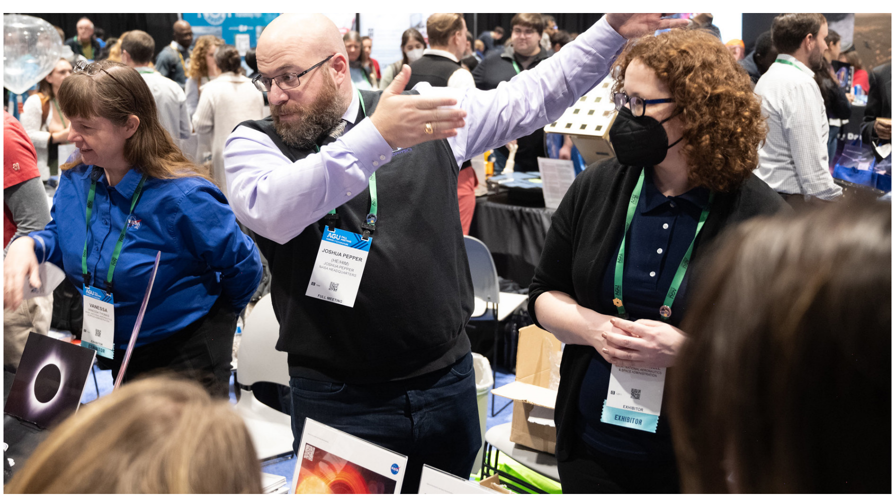

Photo 4. [*Center*] **Joshua Pepper** [NASA HQ—*Transiting Exoplanet Survey Satellite (TESS) Program Scientist*] and [*right*] **Rebekah Hounsell** [GSFC—*TESS Assistant Research Scientist*] discussed the TESS mission with attendees. **Photo credit:** NASA

Photo 5. Dalia Kirshenblat [GSFC—*Science Writer/ Outreach Coordinator*] helped distribute to a throng of eager recipients copies of the always popular 2023 NASA Science Planning Guide. **Photo credit:** NASA

The table area featured 22 programs representing many of NASA's focus areas. The area referred to as "Unlocking the Secrets" was a major draw as it showcased scientific displays of solar system worlds, models of Perseverance rover drill bits, tires, and sample tubes, and other entrancing planetary science exhibit objects—see **Photos 6–7**.

Photo 6. [*Left*] **Kate Manning** [NASA HQ—*Communications Specialist*] and [*right*] **Katherine Schauer** [GSFC—*Strategic Communications Lead*] presented activities related to NASA's Space Communications and Navigation (SCaN) program. **Photo credit:** NASA

Photo 7. NASA staff in the "Unlocking the Secrets" area shared insights with attendees on a variety of displays, including a model of a Mars rover tire [*center left*]. **Photo credit:** NASA

NASA Hyperwall

Lori Glaze [NASA HQ—*Director of the Planetary Science Division*] kicked off Hyperwall-based storytelling on opening night at the exhibit hall, where she presented Planetary Science highlights from 2022 and plans for 2023. Large groups of attendees gathered around the Hyperwall to listen to Glaze and other opening night presenters, which included: **Kartik Sheth** [NASA HQ—*Astrophysics Program Scientist*], **Lawrence Friedl** [NASA HQ—*Director of the Applied Sciences Program*], **Dalia Kirschbaum** [NASA's Goddard Space Flight Center (GSFC)—*Director of the Earth Sciences Division*], and **Nicola Fox** [NASA HQ—*Director of the Heliophysics Division*].[5] Throughout the week, a slew of NASA subject matter experts hosted additional science visualizations and presentations—to view the full schedule see the NASA Hyperwall Science Stories agenda at ***go.nasa.gov/3L9yWfx***. The content covered a wide breadth of topics spanning from the terrestrial to the celestial, including monitoring climate change, weather, and air quality solutions through satellite observations, current and anticipated missions to study solar and extrasolar system worlds, everything there is to know about the Heliophysics Big Year,[6] and much more—see **Photos 8–10**.

[5] **Update:** As of February 2023, Nicola Fox became Associate Administrator for the Science Mission Directorate, replacing Thomas Zurbuchen.
[6] To learn about the Heliophysics Big Year, a global celebration of solar science and the Sun's influence on Earth and the solar system, visit ***solarsystem.nasa.gov/solar-system/sun/helio-big-year***.

Photo 8. Crowds gathered as [far left] **Dalia Kirschbaum** [GSFC] gave a presentation titled "Exploring our Home Planet: from Surf and Turf to Above the Earth" on opening night, December 12. **Photo credit:** NASA

Photo 9. **Nicola Fox** [NASA HQ] shows a "smiling Sun" while giving a talk on the *Heliophysics Big Year*—a global celebration of solar science and the Sun's influence on Earth and the entire solar system. **Photo credit:** NASA

Photo 10. **Alex Young** [GSFC—*Associate Director for Science in the Heliophysics Division*] gave a presentation titled "An Eye on the Sun." **Photo credit:** NASA

NASA Science Now: NASA's New Virtual Exhibit Space Debuts at AGU

Screenshot of the main "lobby" area in NASA's new virtual exhibit space, *NASA Science Now*, which will remain open to the public through 2023. **Image credit:** NASA

NASA's virtual exhibit space, *NASA Science Now* (***go.nasa.gov/NASAScienceNow***), made its debut on December 11, 2022, at the Fall AGU Meeting in Chicago, IL, providing attendees with online access to live and on-demand Hyperwall presentations, science data, and educational resources.

Throughout the week, 249 visitors to the virtual environment "entered" the virtual exhibit via the main lobby [*above*]. From there, they could travel through six unique rooms [four of which are shown *below*]. One room was designated as an Art Gallery; the other five were dedicated to topics including Explore Science, Watch and Learn, Science Data, Fun Zone, and Get Involved. Select Hyperwall presentations were livestreamed in the virtual environment from the in-person NASA Science exhibit—receiving 170 views online.

Screenshot of the Art Gallery room, which was the most visited room in the *NASA Science Now* virtual exhibit during AGU. **Image credit:** NASA

Screenshots of the Science Data room [*left*], Watch and Learn area [*middle*], and Explore Science room [*right*]. (***go.nasa.gov/NASAScienceNow***) **Image credit:** NASA

Broadcasting NASA Science

This year—for the first time ever—NASA Television and the ScienceAtNASA YouTube channel livestreamed a select number of Hyperwall science stories each day of the AGU Fall Meeting. Of the total 67 Hyperwall presentations given throughout the week, 13 of them were broadcast live. The presentations were also livestreamed via the *NASA Science Now* virtual exhibit space, marking another pathway for NASA to share science stories with the public and broaden engagement through virtual initiatives—see **Photo 11**. To watch the 13 livestreamed events on demand, daily listings may be found as follows:

- December 12 – [***youtu.be/7SGvJJ-YIbE***]
- December 13 – [***youtu.be/C9qSz70tI14***]
- December 14 – [***youtu.be/ufQX7I6H_Ug***]
- December 15 – [***youtu.be/OerejWLqbZU]***

Photo 11. **Jason Craig** [NASA/Jet Propulsion Laboratory] was one of thirteen presenters to have their Hyperwall talk livestreamed on NASA Television and the *ScienceAtNASA* YouTube channel. Craig gave a presentation titled "How to Use NASA's Eyes: Real-time 3D of NASA Missions Past, Present, and Future." [*Top*] the view from behind the camera; [*bottom*] Craig giving his presentation at the Hyperwall. **Photo credit:** NASA

For the full listing of Hyperwall science stories, visit the full NASA Hyperwall Science Stories agenda at ***go.nasa.gov/3L9yWfx***.

Included in the Hyperwall science story program were seven special presentations delivered over two days by the winners of the *2022 AGU Michael Freilich Student Visualization Competition*. On December 13–14, **Steve Platnick** [GSFC—*Deputy Director for Atmospheres in the Earth Sciences Division*] and **Kristen Erickson** [NASA HQ—*Director of the Science Engagement and Partnerships Division*] joined AGU representatives to introduce the winners of the competition, which provides an annual opportunity for undergraduate and graduate students to demonstrate creative ways of presenting complex problems in Earth and space sciences through generating data-driven visualizations—see **Photos 12–13**. To view the student visualization presentations, visit ***go.nasa.gov/3YKgJcm***.

Photo 12. [*Far left*] **Steve Platnick** and [*far right*] **Randy Fiser** [AGU—*Executive Director*] stand with several winners of the *Michael Freilich Student Visualization Competition* in between them. From *left to right*: **Lauren Gold** [Arizona State University], **Austin Brenner** [University of Michigan], **Jessica Besnier** [University of Virginia], and **Jieun Kim** [Northwestern University]. These students presented their presentations on the Hyperwall on December 13. **Photo credit:** NASA

Photo 13. [*Far left*] **Kristen Erickson** and [*far right*] **Tracy LaMondue** [AGU—*Vice President, Development*] stand with several other winners of the *Michael Freilich Student Visualization Competition* in between them. From *left to right*: **Benjamin Yang** [Columbia University], **Otto Briner** [University of Illinois–Chicago], and **Christina Last** [Massachusetts Institute of Technology]. These students presented their presentations on the Hyperwall on December 14. **Photo credit:** NASA

Conclusion

With virtual components now almost intrinsic to scientific outreach initiatives, NASA's capacity to share science has never been greater. Hybrid events are the new normal, empowering the SSO to reach larger scientific audiences and the public more than ever before. The SSO will continue to represent NASA at a variety of scientific venues and public events in the coming calendar year, as such hybrid outreach exhibits allow the agency to demonstrate its science activities to audiences across the globe, often reaching thousands of people in the span of a few days. Since the start of the COVID pandemic the SSO—having developed or applied appropriate technology for such hybrid meetings—has reached many individuals who otherwise would not have been aware of or able to participate in NASA's science outreach activities. The SSO staff looks forward to engaging, enriching, and empowering audiences with representations of NASA Science in 2023—and beyond! ■

NASA Holds Discussions about the Future of the EOS Flagship Missions

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Introduction

Over the past two decades, the Earth Observing System (EOS) Flagship missions—which includes Terra (launched December 1999), Aqua (launched May 2002), and Aura (launched July 2004)—provided continuous global observations that have produced a wealth of information on a comprehensive range of Earth system science geophysical parameters, e.g., radiation, clouds, atmospheric state, ocean properties (sea surface temperature, ocean color), trace gases (including those relevant for stratospheric chemistry and greenhouse gases), air quality, natural and anthropogenic aerosols, land-surface hydrology and ecosystem processes, glaciers, and sea ice sheets. Such long-term, consistent, and high-quality time series, or *climate data records*, have become vital for documenting and understanding Earth system processes and climate change. The **Figure** below shows an artist's illustration of the three Flagship platforms.

While their record of accomplishments is evident, all three missions have long exceeded their planned six-year lifetime objectives, and discussions have been underway within NASA's Earth Science Division (ESD) about the inevitable end of these missions. All three Flagships have sufficient fuel and power to operate for at least a couple more years. However, to ensure adequate fuel for collision avoidance and perigee-lowering maneuvers, Terra and Aqua have ceased, and Aura will soon cease, making the *inclination adjustment maneuvers* required to maintain the platforms in tightly controlled, equatorial, Mean Local Time (MLT) polar orbits.[1] In particular, the Terra and Aqua orbits have begun to drift significantly from the closely controlled set overpass times (within about a minute) that they have maintained for the past two decades, with a current MLT drift of approximately -20 and +10 minutes, respectively. Furthermore, Terra—the most venerable of the Flagships—recently had its orbit lowered slightly, and the other Flagships will need to do the same in the next couple of years.

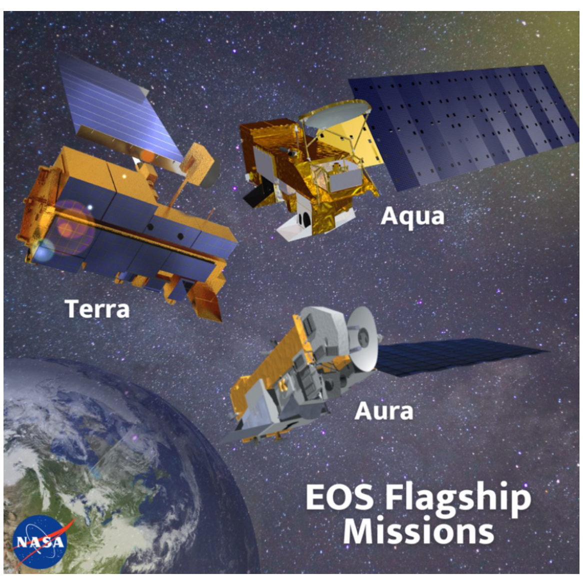

Figure. Illustrations of the three EOS Flagship missions: Terra, Aqua, and Aura. Over the past twenty years, the suite of instruments on these three platforms has provided information on a comprehensive range of Earth system science geophysical parameters. Now, plans are being made for the end of these missions. **Figure credit:** Nyssa Rayne/GSFC

This article provides an overview of two recent virtual meetings that took place to discuss the science and application benefits of continued EOS Flagship observations and the recent Terra orbit lowering maneuver. The first was the virtual *Terra, Aqua, and Aura Drifting Orbits Workshop*, held November 1–2, 2022, the second was the *Terra Lower Orbit Virtual Community Forum* webinar, held on December 8, 2022.

NASA's Terra, Aqua, and Aura Drifting Orbits Workshop

The most recent (2020) NASA Earth Science Division Senior Review for extended missions discussed the continued stellar value of the three EOS Flagship missions, while also recommending further study of science and application possibilities near their end of life.[2] The orbital drift that will take place over the next few years suggests that, for some purposes, future observations may have reduced scientific and application value relative to the long-term data records from the highly controlled, fixed MLT orbits. Yet, at the same time, the platform orbital drift can provide observations of unique scientific and applications utility that would not be possible from the original flagship orbits or through other satellite assets (including non-NASA assets)—for example, from diurnal sampling.

[1] Aura will perform one last series of inclination adjustment maneuvers in April 2023.
[2] The 2020 Senior Review can be viewed and downloaded from ***go.nasa.gov/3YxcPnt***.

In September 2022 NASA Headquarters (HQ) issued a Request for Information (RFI) for a *Terra, Aqua, and Aura Drifting Orbits Workshop* to gather input from the science community to address science that is uniquely enabled by observations made during orbital drift period, as well as the benefits to—and impact on—current societal applications. Responses were to provide input for a virtual workshop that was to be scheduled after the RFI closed.[3]

The RFI and workshop were organized and led by **Lucia Tsaoussi** [NASA HQ, *Earth Science Division—Deputy Associate Director for Research*], **Steve Platnick** [GSFC—*EOS Senior Project Scientist*], **Claire Parkinson** [GSFC—*Aqua Project Scientist* at the time of the meeting, now *Scientist Emeritus*], **Lazaros Oreopoulos** [GSFC—*current Aqua Project Scientist*], **Bryan Duncan** [GSFC—*Aura Project Scientist*], and **Kurt Thome** [GSFC—*Terra Project Scientist*], with assistance from the deputy project scientists and instrument team leads.

There were 109 responses to the RFI, with 32% of the lead respondents having a NASA affiliation (based on email address), 47% from a U.S. institution but not affiliated with NASA, and 21% from international institutions. The organizing team collected and reviewed responses in preparation for the November 1–2, 2022 workshop. The workshop, attended by 546 unique participants over the two days,[4] provided an avenue for the Flagship user communities to gather and participate in discussions about the opportunities—as well as the challenges—presented by the drifting orbits of the Flagship missions.

Workshop Summary

Six two-hour sessions comprised the workshop: three on **Day One** (November 1) and three on **Day Two** (November 2). This included nine parallel instrument breakouts. A brief summary of the workshop follows; the full agenda for the workshop is posted at ***go.nasa.gov/40gTHLA***.

Opening Session

During the first session (**Day One**, **Session 1**) **Karen St. Germain** [NASA HQ, *Earth Science Division—Director*] provided opening remarks and the HQ perspective. **Lucia Tsaoussi** then discussed the workshop goals, and **Steve Platnick** provided a high-level overview of the Flagship missions and a summary of the RFI submissions, including how those submissions were used to inform the workshop agenda.

After the programmatic presentations, each Flagship project scientist [**Bryan Duncan**, **Claire Parkinson**, and **Kurt Thome**] gave an overview of their respective mission's achievements, reviewed the RFI responses relevant to their mission, and discussed possibilities for continued and new science investigations as the MLT orbits drift. At the conclusion of the presentations, there was ample opportunity for participants to ask questions.

Instrument Team Breakout Sessions

The next four sessions (two held on November 1 and two more on November 2) were used for smaller breakout groups that focused on individual Flagship instruments, with two or three breakouts running in parallel during each session. A summary of the breakout sessions is shown in the **Table** on page 14.

Closing Session

The final session (**Day Two**, **Session 3**), moderated by **Lazaros Oreopoulos**, provided an opportunity for the participants to gather for a virtual closing plenary address. The chairpersons of each breakout session—listed in Table on page 14— gave summary reports, followed by questions from participants. **Lucia Tsaoussi** and **Steve Platnick** ended the workshop with some concluding remarks and ideas for potential next steps. Platnick reported that the discussions would form the basis for a report (which is briefly summarized in the next section) to be submitted to NASA HQ that will help inform their decision about the fate of the Flagship missions.

Workshop Report Summary

In the weeks following the workshop, the organizers worked with the Flagship Mission Teams to produce a summary report of the workshop findings. The report is divided into four sections: an executive summary, an overview section, a section that collated individual instrument reports, and a section containing all the workshop plenary presentations.[5]

Some of the key report findings include:

- All operating instruments will continue to provide valuable data while the orbits drift, though some shortwave reflectance-based geophysical retrievals may become more uncertain due to the higher solar zenith angles that come with the drift.
- There is currently no continuity/replacement for the unique midmorning observations from Terra and MLS on Aura.
- Continuing the missions will help monitor unforeseen future events of potentially great impact (e.g., the Hunga Tonga–Hunga Ha'apai volcanic eruption in January 2022).

[3] The RFI can be found at ***go.nasa.gov/3RH0Hwk***.
[4] This number does not include the organizers and instrument leads who convened at GSFC for the workshop.
[5] To read the full report visit ***go.nasa.gov/3mLtvtK***.

Table. *Terra, Aqua, and Aura Drifting Orbits Workhop: Instrument Breakout Sessions, Chairs, and Discipline Leads*. The full report (referenced in footnote 5) provides more details on these breakouts.

Day, Session	Instrument Breakout Group	Chairperson/Discipline Leads
Day 1, Session 2	MODIS-1 (Ocean/ Land)	**Miguel Román** [Leidos—*MODIS Science Team Leader*]/**Bryan Franz** [NASA's Goddard Space Flight Center (GSFC)—*MODIS Ocean Discipline Lead*]; **Chris Justice** [University of Maryland, College Park—*MODIS Land Discipline Co-Lead*]; and **Sadashiva Devadiga** [GSFC—*MODIS Land Discipline Co-Lead*]
Day 1, Session 2	MLS	**Nathaniel Livesey** [NASA/Jet Propulsion Laboratory (JPL)—*MLS Principal Investigator (PI)*]
Day 1, Session 2	CERES	**Norman Loeb** [NASA's Langley Research Center—*CERES PI*]
Day 1, Session 3	MODIS-2 (Land/ Atmosphere)	**Miguel Román/Chris Justice**; **Sadashiva Devadiga**; and **Steve Platnick** [GSFC—*MODIS Atmosphere Discipline Lead*]
Day 1, Session 3	ASTER	**Michael Abrams** [JPL—*U.S. ASTER Science Team Leader*]
Day 2, Session 1	AIRS/AMSU/HSB	**João Teixeira** [JPL—*AIRS/AMSU/HSB Science Team Leader*]
Day 2, Session 1	OMI	**Joanna Joiner** [GSFC—*U.S. OMI Science Team Leader*]
Day 2, Session 2	MISR	**David Diner** [JPL—*MISR PI*]
Day 2, Session 2	MOPITT	**Helen Worden** [National Center for Atmospheric Research (NCAR)—*MOPITT PI*]

***List of Definitions of Acronyms for Flagship Instrument Names** (*in alphabetical order*): *AIRS*—Atmospheric Infrared Sounder; *AMSU*—Advanced Microwave Sounding Unit; *ASTER*—Advanced Spaceborne Thermal Emission and Reflection Radiometer; *CERES*—Clouds and the Earth's Radiant Energy System; *HSB*—Humidity Sounder for Brazil; *MISR*—Multi-angle Imaging Spectroradiometer; *MLS*–Microwave Limb Sounder; *MOPITT*—Measurement Of Pollution in The Troposphere; *MODIS*—Moderate Resolution Imaging Spectroradiometer; and *OMI*–Ozone Monitoring Instrument.

- The missions will provide important overlap for several future Earth science missions.
- The orbital drift will enable observations of processes at different local times for Terra and Aqua (see the report for an extensive list).

Based on this report, representatives from all three Flagships were invited to participate in this spring's Earth Science Division Senior Review.

NASA's Terra Lower Orbit Virtual Community Forum

On December 8, 2022, the Terra Project held the *Terra Lower Orbit Virtual Community* Forum webinar via WebEx. The *Terra, Aqua, and Aura Drifting Orbits Workshop* and resulting report provided the opportunity to inform the community about the changes in crossing time that accompany the end of the inclination maneuvers of the platforms. The workshop also gave the community a chance to discuss new possibilities for science that could be achieved with the changes in crossing time.

Occurring a little over a month after the workshop, the goal of the forum was to provide an update on the Terra Mission's instruments and spacecraft health, mission longevity, and possible science impacts from a recent orbit lowering of the Terra platform.

The forum allowed the Terra Project to inform the community about a set of orbit-lowering maneuvers of the platform that took place October 12 and 19, 2022. NASA's Earth Science Mission Operations (ESMO) Project executed these maneuvers to lower the orbit of Terra by 5.5 km (3.4 mi). This event was an opportunity to inform the user community about these changes and their potential impact on science. The forum was well attended, and a brief summary follows; a video recording of the webinar and a copy of the presentation slide deck are also both available at the Terra website: ***go.nasa.gov/3TGsKyg***.

Forum Summary

Kurt Thome opened the forum with an introductory presentation on the Terra satellite. He provided a brief overview of its 23-year history, including platform health and past orbital maneuvers, and opened discussion of novel research opportunities resulting from Terra's new orbit. The presentation included descriptions of key science from the integration of data from Terra's multiple instruments. The Terra platform and its instruments remain healthy with nearly all subsystems on their primary hardware. Thome highlighted a lunar pitch maneuver to improve calibration quality and the recent solid-state recorder reset that returned the platform to full data capability. While the flight operations team conducted the pitch maneuver and reset, both are key examples of the collaborative efforts of the entire

Terra team that has led to Terra's longevity and the high quality of its data record.

Jason Hendrickson [GSFC, ESMO—*Terra Flight Operations Manager*] followed the Terra introduction with a detailed description of the orbit-lowering maneuver itself. He included a detailed description of past orbital maneuvers, which were used to optimize fuel usage while maintaining the Terra crossing time for more than 20 years. The Terra MLT for its equatorial crossing reached 10:15 AM in September 2022, and this triggered the orbit-lowering maneuver that was the topic of the forum. Hendrickson explained that the orbit lowering was needed at this time to limit close approaches with other missions that are at the same 705 km (~438 mi) orbit used for the Earth sciences constellations (e.g., Aqua and Aura). He provided details on the two-maneuver orbit lowering, instrument configurations during the lowering, and planning that was needed to accomplish the maneuvers—which, as discussed earlier, were executed flawlessly on October 12 and 19. Hendrickson finished his presentation with an overview of how Terra's orbit will evolve in the future from its current 10:15 AM crossing time and 699.5 km (~435 mi) altitude to a predicted 9:00 AM crossing time and 693 km (~431 mi) altitude in February 2026.

The next five presentations were provided by the instrument lead for each of Terra's five instruments, pointing out the minor data impacts resulting (or anticipated) from lowering Terra's orbit.

Helen Worden [National Center for Atmospheric Research (NCAR)]—*MOPITT Principal Investigator (PI)*] provided the MOPITT perspective, highlighting recent carbon monoxide (CO) retrieval results used to quantify different CO sources and to provide information on CO trends, which have shown significant decrease over much of the planet during the period 2002–2010. She explained that lowering Terra's orbit will have minimal impact on such data. The largest impacts will be from changes in surface sampling patterns due to the small decrease in the MOPITT footprint and shifts in ground track and repeat cycle, but those impacts are minimized because MOPITT data products will continue to report location information. The MOPITT data themselves are not strongly affected by orbit changes because thermal infrared data are independent of Sun angle, and Sun-angle effects on the near-infrared products are minimal.

Miguel Román [Leidos—*MODIS Science Team Leader*] presented an overview of MODIS and MODIS data products covering all four MODIS disciplinary focus teams: Atmosphere, Land, Ocean, and Instrument Calibration. Román explained that lowering Terra's orbit to extend active data collection will permit MODIS to cross into a critical 30-year threshold, allowing for more precise delineation of subtle climate trends and analysis of hotspots of change. He stressed that Terra's morning aerosol data collection time provides additional data for afternoon model runs—resulting in fewer forecast errors in the afternoon. Further, he explained that MODIS has enabled the establishment of a long-term (>22-year), consistent data record of the ocean's biological response to major climatic events, as well as several hydrological cycle climatologies. Finally, Román noted that effects on MODIS data because of the orbit lowering were essentially nonexistent and emphasized that effects caused by crossing-time changes will lead to new science. He reiterated that benefits from continuing MODIS collections in Terra's AM crossing time provides intercomparison opportunities and continuity of data records that vastly outweigh any effects created by a decreasing orbit altitude and changes in crossing time.

David Diner [NASA/Jet Propulsion Laboratory (JPL)]—*MISR PI*] gave an update on MISR, highlighting its well-calibrated, moderately high-resolution, multi-angular imaging approach. The MISR sensor design enables a unique set of measurement capabilities, e.g., stereographic cloud-top and smoke/dust/volcanic plume height retrievals; characterizing aerosol particle properties (size, shape, light absorption) over land; and sensitivity to cloud and surface three-dimensional structure. Diner also discussed MISR's role in capturing a long-term record of anthropogenic and natural aerosols—which was used as proof that California's Clean Air Programs have been effective at reducing air pollution in targeted areas. He further illustrated the versatility of MISR data in short-term disaster responses. As an example, he discussed the April 2021 eruption of La Soufrière volcano, in which MISR's plume height map was used to model and inform ash transport forecasts that further contributed to warnings issued by early responders and air quality and air traffic managers.

Diner next described how the orbit lowering has led to a modification of its Level-1 (L1) processing—to account for the fact that Terra no longer maintains a Worldwide Reference System-2 (WRS-2) ground track. He explained that this algorithm change has already been implemented and that the impacts on spatial footprint, swath, and sensor view angles will be negligible, and that will be distributed according to the closest WRS-2 path. Diner showed multiple examples of how the change in crossing time can have impacts on MISR products but also explained how the change in crossing time will lead to new science because of those effects. He closed by emphasizing that there is no other instrument with this combination of capabilities currently in orbit and no replacement is envisioned in the near term. Thus, as with MODIS, any effects from orbital changes are far outweighed by the opportunities to continue data collection with MISR.

Norman Loeb [NASA's Langley Research Center—*CERES PI*] provided an overview of the CERES instrument's long-term, integrated global climate data record (CDR) of Earth's radiation budget (ERB) from the surface to top-of-atmosphere (TOA) altitudes together with the associated cloud, aerosol, and surface properties. He also explained that for the past 15 years the CERES angular distribution models (ADMs) have been a valuable community science resource, and that the new drifting orbit will allow for additional extended angular measurements that can be used to calibrate future instruments orbiting in unique paths. Loeb noted that—due to the nature of the CERES products being spatial and temporal combinations of multiple datasets, along with the corrections provided by the ADMs—there would be no impact to CERES data from the orbital lowering. Furthermore, Loeb emphasized that extending Terra's lifetime significantly reduces the risk of a data gap while the CERES team awaits the launches of follow-on sensors (e.g., Libera —the first Earth Venture Continuity mission) while generating new science opportunities.

Michael Abrams [JPL—*ASTER Science Team Leader*] presented an overview of ASTER, an instrument that captures stereo coverage of surface topography for use in generating digital elevation models (DEMs), as well as multispectral thermal infrared data, for use in studying volcanic eruptions, land changes in coastal ecosystems, wildfires, alpine glacier extent, and the development of an urban heat island climatology. Abrams summarized the minor potential impacts of the orbit lowering on ASTER data collection, leading to changes to spatial resolution, swath, and higher-level product resampling. The L1A and L1B data products will have a slight change in spatial resolution (averaging ~1%) as it improves in cross-track direction (as ASTER is closer to the surface) but decreases in the along-track direction because Terra speeds up slightly at the lower altitude. The swath width becomes slightly narrower, and with the resolution changes there is impact to the orthorectified L1T product, which will be resampled in a way to maintain the current spatial resolutions. Likewise, higher-level products will be similarly resampled. Expected impacts are minimal because of the cubic convolution resampling of the higher-level products to orthorectify the data. One additional key point is that there will be no impact to the DEM products after orbit lowering, because those products are produced after ortho processing, and the geometry of the fore and aft views remains constant.

Kurt Thome concluded the presentations with a wrap-up summary of the material presented during the forum, including what is next for the Terra platform in terms of orbit altitude and crossing time. The health of the platform and instruments will allow Terra instruments to be operated until the project is directed to enter Phase F, at which point the instruments will be closed out, final perigee-lowering maneuvers will take place—consuming all remaining fuel, the platform will be passivated, and the Project Science Office will undertake the data close-out process.

An open period for questions or comments from the community followed the presentations. Questions focused on data processing and continuity, future novel applications of Terra data, and the updated, unreleased future timeline for EOS missions.

Conclusion and Next Steps

NASA HQ's intent in issuing the RFI and organizing the *Terra, Aqua, and Aura Drifting Orbits Workshop* was to help inform their deliberations about the value of the Flagship missions over the next couple of years. The strong community engagement, both in terms of the submitted RFI responses and workshop participation, accomplished this goal, with all three missions being invited to the 2023 Senior Review.

The *Terra Lower Orbit Virtual Community Forum* provided an opportunity to follow up on the discussions that began at the *Terra, Aqua, and Aura Drifting Orbits Workshop* and delve deeper into the specific details of relevance to the Terra user community on the impact of lowering Terra's orbit.

As a follow-on to the *Terra, Aqua, and Aura Drifting Orbits Workshop*, NASA released a complementary RFI focusing specifically on data continuity for the Flagship missions—with responses due by April 4, 2023.[6] While the exact end date for each Flagship mission is yet to be determined pending the outcome of the next Earth Science Senior Review, it is clear that they are all nearing their end of life. It is therefore critical that the research and applications communities that have relied on the continuous availability of datasets from the Flagship instruments for the past two decades plan now to identify and test alternative datasets. For several ROSES cycles,[7] NASA has supported algorithm continuity product development and production to bridge those EOS data records that are obtainable from Suomi National Polar-orbiting Partnership (NPP) and Joint Polar Satellite System (JPSS) sensors.[8] The RFI seeks to gather input from the community on these data continuity products, to identify gaps and/or alternative data sources, and to determine possible further actions to facilitate transition to the post-Flagship era.

Community input from this RFI will be considered in developing, planning, and implementing a *Terra, Aqua, and Aura Data Continuity Workshop* in the spring of 2023. ■

[6] The RFI can be viewed at ***go.nasa.gov/40eAfz0***.
[7] ROSES stands for Research Opportunities in Space and Earth Science.
[8] The NOAA-20 and NOAA-21 missions are JPSS launches. They were renamed after launch and initial checkout.

Summary of the 2022 Sun–Climate Symposium

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Introduction

Unlike recent years when COVID-19 necessitated virtual meetings, the 2022 Sun-Climate Symposium was an in-person meeting—with a few prerecorded presentations from those who either could not or chose not to attend in person. The meeting took place at the Concourse Hotel in Madison, WI, from May 16–20, 2022. It marked the seventeenth in the series of symposia that started as Solar Radiation and Climate Experiment (SORCE) Science Team Meetings in 1999. There was participation from many aspects of the Earth atmosphere, climate, solar-variability and stellar research communities in this multidisciplinary, international Sun–Climate Symposium. The **Photo**, left, shows the Symposium participants.

Photo. Attendees at the 2022 Sun–Climate Symposium at the Concourse Hotel in Madison, WI. **Photo credit:** Kelly Hepburn/ Laboratory for Atmospheric and Space Physics (LASP)

Meeting Overview and Theme

The theme of the 2022 Symposium was *Improved Climate-Record Reconstructions from Solar Variability and Earth System Observations*. The rationale for choosing this theme is that climate studies require records of longer duration than most direct individual measurement sources (e.g., a single instrument, observer, or site) provide. Time series of adequate duration to study climate—called *climate data records*—can be created by combining measurements from different observers, sites, or instruments. However, such combinations are not as easy as simply combining all the sources into a single time series. Establishing climate-data records requires determining the correlations between all of the individual measurement sources that comprise the data record. Once these correlations are established, however, the benefits are well worth the effort. These lengthier time-series, or *reconstructions*, serve as proxies for the climate itself as well as the natural and anthropogenic influences acting upon the climate.

The presenters at the Symposium explored reconstructions and the understanding that can be gained from them, with emphases on links between climate influences—particularly the natural driver provided by solar variability—and the Earth-climate system. These studies include improvements in recent and upcoming climate, atmosphere, and radiative observations and models—as those are often the most accurate tie points of historical reconstructions; correlations between various records used as proxies for historical reconstructions—as those provide the long-duration records needed for climate studies; new methodologies for extending or combining records; and studies of the climate variability associated with these records.

Meeting Format

The meeting opened with a short Programmatic Perspectives session that included words of welcome, updates on the status of current missions—and one follow-on in development—and perspectives from NASA Headquarters (HQ) on NASA's overall Sun–Climate portfolio. The bulk of the meeting consisted of six oral sessions (topics listed below) as well as a poster session. There were also two optional tours offered during the meeting—to learn more, see *Group Tours Highlight Unique Archeological Sites and Distinctive Architectural Style in Madison* on page 26.

The 2022 Sun–Climate Symposium was organized around the following topics (corresponding to the six oral sessions):

- Recent Observations and Methods for Improving Climate Record Reconstructions;
- Measurements and Models of Solar and Climate Variability;
- Long-Term Atmospheric Measurements;
- Stellar Variability and Connections to the Sun;
- Next-Generation Observations and Models for Sun and Earth; and
- Improved Solar Reference Spectra: Implications for Remote Sensing and Radiative Transfer.

Most of the 2022 Sun–Climate Symposium presentations are available online at ***lasp.colorado.edu/home/meetings/2022-sun-climate-symposium/2022-scs-science-program-agenda***.

Programmatic Perspectives: Long-term Solar Irradiance Measurements and Continuity

Tom Woods and **Peter Pilewskie** [both from the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP)] opened the Symposium with some words of welcome and logistics.

Erik Richard [LASP] then provided an update on the status of the Total and Spectral Solar Irradiance Sensor–1 (TSIS-1) and on plans for TSIS-2. He also provided updates on the Compact Solar Irradiance Monitor (CSIM) and Compact Total Irradiance Monitor (CTIM) CubeSat missions.[1] Richard highlighted the many achievements over the nearly two decades of measurements from the Solar Radiation and Climate Experiment (SORCE) to the present, including contributions of improved accuracy in solar spectral irradiance from the TSIS-1 Spectral Irradiance Monitor (SIM) to the success of next-generation sensors like CSIM—see **Figure 1**, below, to compare CSIM data with those from TSIS-1 SIM.

David Considine [NASA HQ—*Manager, Modeling, Analysis, and Prediction Program*] then gave the perspective from NASA HQ, providing an overview of NASA's Sun–Climate missions and research projects. For the sake of completeness, future missions are discussed in the summary for Session 5: *Next-Generation Observations and Models for Sun and Earth*, beginning on page 24.

Session 1: Recent Observations and Methods for Improving Climate Record Reconstructions

Presenters in the opening session examined current long-term climate records and reconstruction methods for producing the next-generation records. Long-term reconstructions needed for climate studies invariably

[1] To learn more about how NASA has utilized CubeSats for Earth Science research, see "CubeSats and Their Roles in NASA's Earth Science Investigations," in the November–December 2020 issue of *The Earth Observer* [**Volume 32**, **Issue 6**, pp. 5–17—***go.nasa.gov/3tmwAig***].

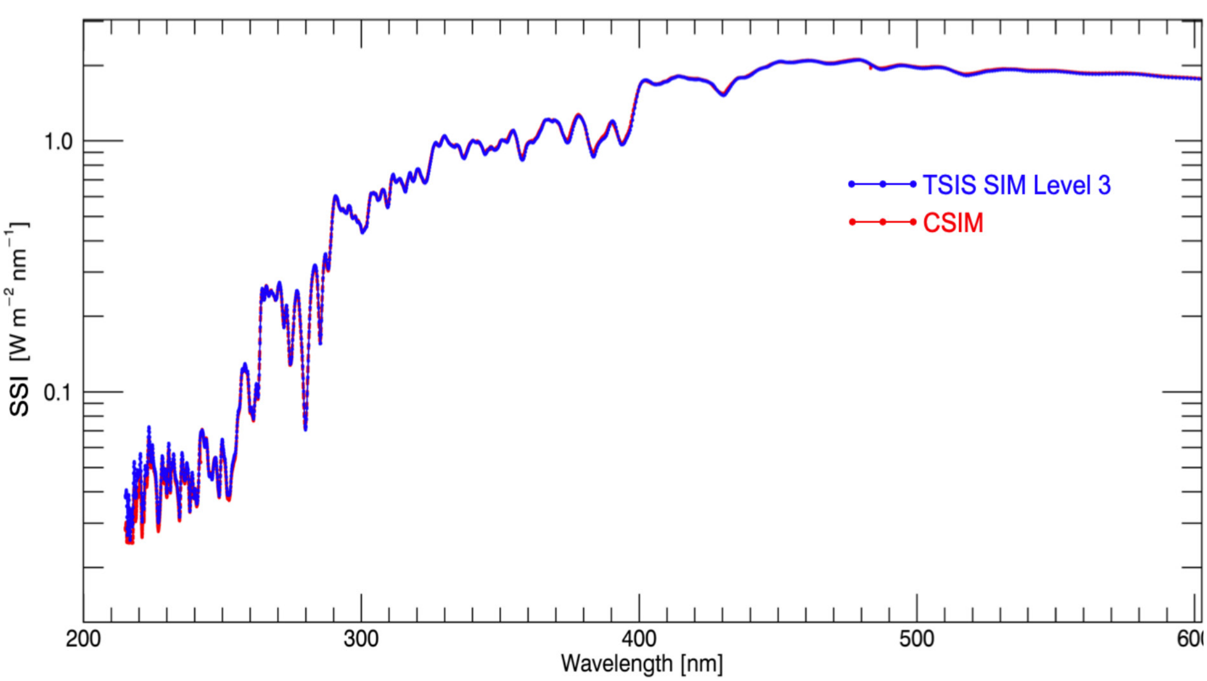

Figure 1. Comparison of three weeks of continuous solar irradiance from 210–600 nm daily spectra from the Compact Solar Irradiance Monitor (CSIM) CubeSat and Total Solar Irradiance Spectrometer–1 (TSIS-1). Both spectra are plotted on their native irradiance scales with no scaling or offsets applied. Agreement is better than 0.5%. **Figure credit:** Erik Richard/LASP

require multiple input datasets. Combining such datasets necessitates accounting for biases, drifts, and spurious signals in overlapping data, as well as approaches to span data gaps, e.g., proxies and models. Discussion topics included updates to observational data, methods of producing composites both temporally and spectrally, gap filling, and temporal extensions via models.

Timothy Jull [University of Arizona] opened the session with a keynote presentation on the radiocarbon (^{14}C) record that exhibits rapid changes of up to 20% as manifested in tree rings, caused by transient increases in the ^{14}C production rate that may be due to a mix of solar energetic particles and other astrophysical phenomena, such as gamma ray bursts and geomagnetic excursions. Jull and his colleagues have developed new annual and subannual ^{14}C datasets from tree rings from diverse geographical locations to confirm these phenomena. This work shows that the intensity and structure of the ^{14}C signal is multifaceted, thereby complicating our understanding of the forcing and attribution to the underlying astrophysical events.

Laure Lefevre [Royal Observatory of Belgium's World Data Center for Sunspot Indices and Long-term Solar Observations (SILSO)] spoke next, focusing on reevaluations and reconstructions of sunspot number. In addition to presenting an historical review of revisions of existing datasets, he discussed the reconstruction of the International Sunspot Number from raw sunspot data, including a large effort to gather raw data from around the world, stitching together historical and modern sunspot numbers (SN), and evaluating the quality of the reconstructed series through advanced statistical techniques.

Frédéric Clette [SILSO] discussed the F10.7 cm radio flux, which is one of the primary long-term indices of solar activity and a proxy for the Sun's ultraviolet (UV) irradiance for various ionospheric models and predictions. F10.7 plays a unique role in understanding the long-term Sun–Earth coupling.

Theodosios Chatzistergos [Max Planck Institute for Solar System Research, *Germany*] discussed how data from dark sunspots and more diffuse bright structures called *faculae* must be augmented by indirect measurements of solar magnetism, such as are obtained from measurements of strongly ionized calcium's (Ca II) K spectral line measurements—which extend back to 1892. Chatzistergos provided an overview of the existing Ca II K archives along with methods for their photometric calibration for use in studies of past solar variability and irradiance.

Ted Amdur [Harvard University] described creating a stable reconstruction of TSI data over the satellite era—many of which are challenged by coverage gaps, systematic observational biases, and drift in satellite observations. Amdur and his team used monthly observational data from 1980–2021 from satellites and magnetic activity proxies to generate a stable, joint estimate of both TSI and the error structure of observing instruments that address these problems, showing secular changes in both the amplitude of the 11-year solar cycle and TSI data during cycle minima.

Greg Kopp [LASP] gave an overview on the status of the latest TSI measurements from the TSIS-1 Total Irradiance Monitor (TIM), the highest accuracy TSI instrument in the uninterrupted, 43-year-long TSI climate data record. Kopp then showed how the space-era measurement record is extended back in time using the Advective Flux Transport model to simulate solar activity over the last 300 years. This is based on the latest SN records and the Naval Research Laboratory's Total Solar Irradiance (NRLTSI) proxy model.

Kalevi Mursula [University of Oulu, *Finland*] concluded the session with a prerecorded presentation on what appear to be long-term increases in the visible (VIS) part of the solar spectrum apparent in SORCE SIM data that had been adjusted via correction by TSIS-1 SIM.

Session 2: Measurements and Models of Solar and Climate Variability

Observations of the Sun from space over the past more than four decades—and more than three solar cycles—have provided new insight in solar variability and its influence on terrestrial atmosphere. What are the key science questions that will advance our understanding of Sun, climate, and climate variability? How well do climate models address those key questions? What are the current uncertainties in measurements of Sun and climate? To address these questions, Session 2 was devoted to challenges and accomplishments in measurements and models of Sun and Earth's system, and possible links in Sun–Earth connection.

Gavin Schmidt [NASA's Goddard Institute for Space Studies (GISS)—*Director*] gave the keynote address for this session, in which he discussed historical drivers of climate change in the GISS Earth System Model. Climate models in general are improving in skill as they increase in complexity. More complete representations of atmospheric chemistry and tropospheric–stratospheric coupling as well as higher resolution result in better representation of keys modes of internal climate variability. Attributions of short-term (e.g., volcanic), decadal (e.g., solar), and long-term trends (e.g., greenhouse gases and aerosols) are all now clear. Analysis conducted using models has confirmed climate impacts over the span of solar cycles in the stratosphere but impacts in the troposphere and surface are less clear due to ocean–atmosphere coupling.

Lynn Harvey [LASP] discussed the current state of understanding the role of the polar vortex in coupling between different atmospheric layers by "bottom-up" and "top-down" processes. For bottom-up coupling, the polar vortices couple the atmosphere from the ground to geospace by shaping the background wind field through which atmospheric waves propagate. For top-down coupling, energetic particle precipitation (EPP) generates nitrogen oxides in the mesosphere and lower thermosphere over the polar regions. Harvey showed examples from observations and in whole atmosphere models to elucidate both the top-down and bottom-up coupling processes.

Lon Hood [University of Arizona, Lunar and Planetary Laboratory] continued the upper-atmosphere theme. He discussed a tropical convective disturbance known as the Madden–Julian Oscillation (MJO) that is modulated by upper-atmospheric conditions, and driven by the quasibiennial oscillation (QBO) and the 11-year solar cycle. Current global climate models fail to simulate the QBO–MJO connection, and it is also doubtful that they are able to simulate the solar–MJO connection.

Marty Mlynczak [NASA's Langley Research Center (LaRC)] reported that between 2002 and 2020 the mesosphere and lower thermosphere (M/LT) have cooled and contracted due to increasing concentration of carbon dioxide (CO_2) and steadily declining solar activity. The M/LT has cooled about 3.5 K [3.5 °C (6.3 °F)] since the start of the Industrial Age; indeed, the 2018–2020 annual global average temperature was the coldest over the entire period. In addition to these connections to climate change, the expanding space economy in low Earth orbit depends on knowing the variability and long-term changes of many aspects of the geospace environment.

Jae Lee [University of Maryland, Baltimore County (UMBC)'s Joint Center for Earth Systems Technology (JCET)] considered how mean quantities in Earth's shortwave (SW) radiative energy budget may be skewed by their spatial variabilities, which are not distributed normally. In observations from the Multi-angle Imaging Spectroradiometer (MISR) on Terra and from the various Clouds and Earth's Radiant Energy System (CERES) instruments,[2] the global median value of the shortwave irradiance is ~3 W/m^2 less than global mean, due to the positive skewness of the distribution. Moreover, probability distribution functions (PDFs) may change with time and location. The global mean top-of-atmosphere (TOA) irradiance derived from MISR is about 7 W/m^2, or about 7% less than CERES measured irradiance during the last two decades. While the characteristics of the two datasets agree qualitatively, differences in the regional PDFs are most apparent over high-cloud regions.

Xianglei Huang [University of Michigan] shifted the discussion from the TOA to the surface, as he explained how important the spectral distribution of incoming solar irradiance is to the surface climate. While TSI measurements from TSIS-1 differ from those used in the climate models used in the sixth Climate Model Intercomparison Project (CMIP6) by no more than 1 W/m^2, the spectral irradiance difference between a given VIS and a near-infrared (NIR) band can be as large as 4 W/m^2—and with opposite signs. Huang showed that different VIS and NIR partitioning can affect the simulated climate, underscoring the importance of continuously monitoring SSI and the use of correct SSI in climate simulations.

Tom Woods [LASP—*TSIS-1 Principal Investigator*] presented SORCE solar variability results observed during Solar Cycles 23 and 24. Comparing solar cycle minimum levels in 2008–2009 to those in 2019–2020, Woods showed differences that were insignificant when considering instrument stability over the 11-year period. When the SORCE solar cycle variability results were compared to those from TSIS-1 (2018–present), there were notable differences for wavelengths longer than 1600 nm. While the improved accuracy from TSIS-1 SSI should resolve most of the remaining differences, the low-level solar cycle 25 activity to date does not provide enough variability to adequately address the differences.

Wolfgang Finsterle [Physikalisch Meteorologisches Observatorium Davos, World Radiation Center (PMOD/WRC), *Switzerland*] presented an update on VIRGO[3] TSI time series using a new data-driven approach to correct the measurements for long-term instrument degradation. He proposed that similar data-fusion methods could combine the measurements from different TSI experiments and that the statistical properties of the composite could be used to forecast future TSI variability.

Sergey Marchenko [NASA's Goddard Space Flight Center (GSFC)/Science Systems and Applications, Inc. (SSAI)] presented results of an investigation into what drives TSI changes during a *deep solar minimum*—when detectable sunspots and long-lasting active regions are absent. He used TSI data on magnesium (Mg II) activity indices (proxies for solar activity), extreme UV (EUV) irradiance, and magnetograms to show that TSI closely follows the changes in the total magnetic flux of the sources. Marchenko concluded that TSI during more-extended deep minima, e.g., what occurred

[2] CERES instruments presently fly on the Terra (Flight Models (FM)-1 and -2), Aqua (FM-3 and -4), Suomi National Polar-Orbiting Partnership (FM-5), and NOAA-20 (FM-6) platforms.

[3] VIRGO stands for Variability of solar IRradiance and Gravity Oscillations, an experiment on the joint European Space Agency–NASA Solar and Heliospheric Observatory (SOHO).

during the extended, low sunspot number period of the Maunder Minimum (1645-1715), may have been lower than the previous solar minimum in 2008.

Marty Snow [South African National Space Agency] presented an overview of the in-flight calibration of the 17-year (2003–2020) SORCE–SOLSTICE UV solar spectral irradiance, along with the solar variability results from the final data release in version 18 of the data product. The data agree with the TSIS-1 SIM within 5% throughout the 200–300 nm overlap region; there is qualitative agreement with the Spectral and Total Irradiance Reconstruction—Satellite era (SATIRE-S) irradiance model at wavelengths shorter than 260 nm.

Serena Criscuoli [National Solar Observatory (NSO)] presented results of an investigation into the variability of solar hydrogen *Balmer lines*—sensitive indicators of the physical conditions in the solar atmospheres—observed by OSIRIS,[4] SCIAMACHY,[5] OMI,[6] and GOME-2,[7] combined with high-resolution data from the NSO's ground-based Integrated Sunlight Spectrometer.

Andrea Diercke [NSO] described how she used solar imaging of the chromospheric hydrogen Lyman-α spectral line (H-α) as a tracer of solar activity and compared the results to other established tracers like relative sunspot number, F10.7 cm radio flux, and the Mg II index. She explained H-α is a strong line in the spectrum of the Sun and other stars and is already used as a powerful tracer of magnetic activity. For the Sun, other tracers are typically used to monitor solar activity. Nonetheless, the Sun is observed constantly in H-α with globally distributed ground-based, full-disk imagers.

The final two presentations in this session explored new ways of considering the solar cycle.

Robert Leamon [University of Maryland, Baltimore County] posited that *terminators*—the endpoints of the Hale Cycle (the 22-year progression of magnetic activity)—provide a new, and more insightful way of looking at timing solar cycles than counting spots. Terminators can be used to construct a new solar-cycle phase clock, which maps all solar magnetic activity onto a single normalized epoch.

[4] OSIRIS stands for Optical Spectrograph and InfraRed Imaging System, a Canadian instrument flying on Sweden's Odin satellite.

[5] SCIAMACHY stands for SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY, an instrument that flew on the European Space Agency's ENVironmental SATellite (ENVISAT) mission.

[6] OMI stands for Ozone Monitoring Instrument, a Dutch instrument on NASA's Aura platform.

[7] GOME-2 stands for Global Ozone Monitoring Experiment-2, an instrument flying on the European METOP-A satellite series.

Scott McIntosh [NCAR] discussed the first six post-terminator months in solar cycle 25, exploring the consequences of the transition into solar cycle 25, and what might be expected in the remainder of the cycle.

Session 3: Long-Term Atmospheric Measurements

As meteorological satellites evolved from the early imaging satellites [e.g., the Television Infrared Observation Satellite (TIROS-1), in 1960] to include atmospheric sounding capabilities, advanced computers combined with better atmosphere radiative transfer theory enabled satellite data to make important contributions to weather forecasting and global climate change research. The continuous global observing capabilities of Earth observing satellites enhanced monitoring of the global atmospheric state (e.g., temperature, moisture, wind), predicting weather processes and events, estimating the global radiation energy budget, monitoring global ocean conditions and ocean–atmosphere interactions, observing land and biosphere seasonal trends, evaluating the changes in atmospheric trace gases, monitoring global climate change, and other Earth System phenomena. The presenters in this session focused on the long-term changes observed in the Earth-atmosphere system by satellites as well as in situ observations to put them in the context of simultaneous solar changes.

Norman Loeb [LaRC] opened the session with a keynote presentation on tracking changes in Earth's energy flows. He explained that Earth's climate is determined by a delicate balance between how much of the Sun's energy Earth absorbs and how much thermal infrared radiation Earth emits to space. Continued increases in concentrations of well-mixed greenhouse gases in the atmosphere have resulted in a net gain of energy, and hence, warming, on Earth. Loeb showed how satellite observations from CERES, which date back to 2000, and *in situ* measurements of heating within the climate system were used to track changes in *Earth's Energy Imbalance* (EEI) since 2000, as shown in **Figure 2** on page 22. Both observing systems show a remarkable doubling of EEI between mid-2005 and mid-2019 that is attributable to anthropogenic forcing and internal variability.

Anne Sledd [University of Colorado, Cooperative Institute for Research in Environmental Sciences (CIRES)] looked at the influence of clouds on solar radiation in the rapidly changing Arctic. She explored the impacts of clouds on solar radiation in the Arctic, using both satellite observations and global climate models (GCMs), and found that clouds actually contribute more to the TOA albedo than the surface.

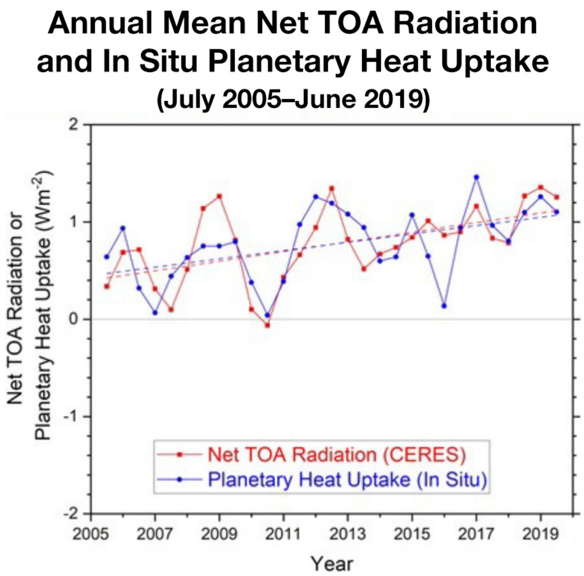

Figure 2. CERES net radiation and *in situ* planetary heat uptake data show consistent increasing trends with good agreement in year-to-year variability. They independently show an approximate doubling of Earth's Energy Imbalance (EEI) from mid-2005 to mid-2019. Dashed lines correspond to least squares linear regression fits to the data. **Figure credit:** Norman Loeb/LaRC, from an article published in *Geophysical Research Letters* (***doi.org/10.1029/2021GL093047***)

Andrew Heidinger [National Oceanic and Atmospheric Administration's (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS)] presented an overview on Geostationary Operational Environmental Satellite (GOES) climate activity at NESDIS. GOES is an emerging source of Fundamental Climate Data Records (FCDRS), including solar reflectance applications. There are several projects underway that are improving older GOES data (1975–2020). The International Satellite Cloud Climatology Project Next Generation (ISCCP-NG) is pioneering a new way to provide the climate community with easy access to the advanced capabilities of current geostationary imagers. The next installment of GOES (GeoXO) will bring new sensors to the GOES Community.

Steve Platnick [GSFC, Earth Sciences Division—*Deputy Director for Atmospheres* and *Moderate Resolution Imaging Spectroradiometer (MODIS) Atmospheres Discipline Team Lead*] presented an overview of recent time series analyses for the MODIS standard and Visible Infrared Imaging Radiometer Suite (VIIRS)/MODIS continuity products.[8] Now that a two-decade data record has been obtained from the MODIS sensors, cloud datasets are just beginning to be useful for climate analysis. However, the utility of the data records for this purpose fundamentally depends on instrument stability as well as the capability to distinguish interannual variability from longer-term secular trends. An additional challenge is in continuity across the Earth Observing System MODIS and and Suomi National Polar-orbiting Partnership (Suomi NPP)/Joint Polar Satellite System (JPSS) VIIRS cloud records, given the substantial spectral channel differences between the sensors.

Larrabee Strow [UMBC, Department of Physics and JCET] gave an overview of how the stability of the Atmospheric Infrared Sounder (AIRS) is quantified, and what steps can be taken to improve its radiance record, which is now being supplemented with data from the Crosstrack Infrared Sounder (CrIS) sensors flying on Suomi NPP and on the operational NOAA-20 satellite. Strow presented relatively simple, radiance-oriented analysis approaches that show promise for climate trend estimates and variability, including surface temperature, temperature and water vapor profile trends, and cloud forcings.

Eva Borbas [University of Wisconsin, Madison's (UWM), Space Science and Engineering Center (SSEC)] described her work on inferring global cloud and moisture properties from the four-plus-decades long High-resolution Infrared Radiation Sounder (HIRS) data record. Results show significant latitudinal differences in total precipitable water vapor (TPW). Borbas explained that the resultant 45-year data record of cloud and moisture properties will provide an opportunity to examine potential connections between the HIRS upper tropospheric humidity record and the solar cycle.

Jacola Roman [NASA/Jet Propulsion Laboratory (JPL)] described the importance of assessing possible outcomes from global climate models as imperative for resiliency and adaptation to climate change. Roman described a *nonparametric multivariate regression method* to detect and rationalize trends and to assess temperature trends from AIRS–Advanced Microwave Sounding Unit (AMSU) against the highly accurate Global Positioning System–Radio Occultation (GPS-RO) retrievals and to reanalyze longer-term observations.

Matthew DeLand [GSFC/SSAI] described how the response of polar mesopheric clouds (PMC) to variations in solar activity has decreased in recent decades—even as overall PMC activity has been increasing. He reviewed these results and updated the record with recent measurements from the early part of Solar Cycle 25. PMCs are noteworthy because aspects of their characterization are correlated with solar activity.

Ningchao Wang [LaRC] described how his team will derive new nitric oxide (NO) cooling rate data by considering only the NO emission from the fundamental band. Since 2002, NO cooling rates have been routinely derived from measurements made by the Sounding of the Atmosphere using Broadband

[8] MODIS flies on NASA's Terra and Aqua platforms. VIIRS flies on Suomi National Polar-Orbiting Partnership (Suomi NPP) and JPSS-1 (renamed NOAA-20 upon reaching operational status).

Emission Radiometry (SABER) instrument on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite. Preliminary results show that, below 160 km (~99 mi), the change of the NO cooling rate is within 5% during the most recent solar maximum year (2014) and is up to 12% during the solar minimum in 2009 with respect to the currently available NO cooling data.

Susan Nossal [UWM] showed how multidecadal observations reveal a repeatable and statistically significant solar cycle response in the Balmer H-α intensity—with the caveat that some datasets are limited and have calibration uncertainties. She discussed strategies used to merge observations, calibrate the data, reanalyze older spectra, and assess uncertainties, as well as plans to extend the dataset. Nossal also presented simulations using the National Center for Atmospheric Research's (NCAR) Whole Atmosphere Community Climate Model-eXtended (WACCM-X) which predict that thermospheric hydrogen will increase in response to the rise of CO_2 and methane (CH_4), and that the response of hydrogen would be larger during lower solar activity conditions.

Session 4: Stellar Variability and Connections to the Sun

Stellar variability and *asteroseismology*—the study of oscillations in stars—are quickly growing fields of research due to recent photometric studies from exoplanet-finding missions. These studies give insights into solar variability as well as effects on planetary climate and habitability. Selection effects involving stellar rotation rates and *metallacites* (the amount of elements heavier than hydrogen and helium that are present) help refine the list of solar-like stars and indicate how "star-like" the Sun is and where it lies on its evolutionary activity and spin-down track (i.e., slowing of solar rotation). Presenters in this session discussed these new stellar-variability findings and their insights into the Sun's behavior.

There were also presentations that focused on the climate conditions that allowed for life to emerge on early Earth, and the possibilities that other inner planets in our Solar System also supported habitable conditions early in their histories. Answering this question is central for answering the fundamental question: *Are we alone in the Universe?* Scientists seek to understand whether Earth could be a special outlier, or whether it is a "typical" rocky planet. This requires understanding the role the young Sun played in supporting the basic requirements for life as we know it on Earth, including persistent external energy fluxes as well as the presence of liquid water and organic compounds that promoted the emergence and complexification of biological systems on early Earth.

Alexander Shapiro [Max-Planck Institute for Solar System Research (MPISSR), *Germany*] gave the keynote address in this session, in which he covered the broad topic of the solar–stellar connection. Since the Sun is the only star where fundamental processes take place over resolvable spatial scales, it provides a perfect testbed to understand conditions in stellar atmospheres. Shapiro explained that it is now possible to extend the models originally developed for and tested against the Sun to model stellar atmospheres because of enormous recent progress in solar observations and models.

Vladimir Airapetian [GSFC, Sellers Exoplanet Environment Collaboration (SEEC)/American University] described how interdisciplinary research methodologies and tools of heliophysics, astrophysics, and planetary and Earth science can be applied to address the complex question: *Are we alone in the Universe?* Recent data from the Hubble and Kepler Space Telescopes have opened a new avenue in reconstructing the life of the young Sun using observationally constraining state-of-the-art theoretical models of the coronal and wind environments in young solar-like stars.

Benjamsdin Montet [University of New South Wales, *Australia*] explained how observations from the Kepler and Transiting Exoplanet Survey Satellite (TESS) Astrophysics missions provide opportunities to understand stellar variability on timescales from a few seconds to more than a decade. Analyses of these data have helped advance understanding of the magnetic evolution of Sun-like stars over billions of years.

Nina-Elisabeth Nemec [Georg-August-Universität Göttingen, *Germany*] explored the phenomenon of why magnetic fields of the active Sun and other cool stars show increased numbers of spots. She summarized research spanning several decades, which has revealed that with increasing spot coverage (and hence, activity level), the coverage of faculae increases less rapidly, leading to a decrease in the facular-to-spot area ratios with increasing activity level.

Sowmya Krishnamurthy [MPISSR] discussed the *S-index*—which is a measure of the chromospheric emission-line cores of calcium (Ca II), hydrogen (H) and potassium (K). He explained that S-index serves as a proxy for the magnetic activity of a star, particularly solar-type and cooler stars, and depends not only on the intrinsic stellar properties (e.g., metallicity) but also on the stellar inclination, as the amplitude of S-index variations decreases with decreasing inclination. The Sun, for example, has a completely normal level of S-index variability when compared to stars with similar magnetic activity. The observed S-index also decreases with increasing metallicity, a dependency that is reproduced well in models.

Cecilia Garraffo [Harvard–Smithsonian Center for Astrophysics] concluded the session with a presentation on stellar high-energy radiation effects on exoplanets. One primary finding was that older, more massive type-M dwarf stars should have better conditions for life in their habitable zones than very low-mass, typically very active stars that expose their planets to much stronger high-energy radiation than we experience on Earth. In addition to improving stellar age estimates, there is a need for observations of stellar variability in the extreme UV portion of the spectrum.

Session 5: Next-generation Observations and Models for Sun and Earth

Presenters in this session reviewed current and next-generation solar and terrestrial observations and models. With the rapid advancement in the development of miniaturized satellites (e.g., CubeSats) and sensors (e.g., CTIM and CSIM), lower-cost constellations can be expected to provide more complete global and temporal coverage. Throughout, continuity of climate records must be maintained while providing new observables to address the many questions about climate change and its effects on our society.

Tristan L'Ecuyer [UWM] opened the session with a keynote address on the Polar Radiant Energy in the Far Infrared Experiment (PREFIRE), which is being developed as an Earth Venture Instrument mission.[9] He explained that PREFIRE aims to reduce uncertainties in the polar energy budget—which has substantial implications for predicting changes in sea ice cover, precipitation, ice sheet dynamics, and surface mass balance. PREFIRE observations will cover more than 95% of the energetically relevant portion of the infrared spectrum—including wavelengths longer than 15 µm that have never been systematically observed from space.

Graeme Stephens [JPL] spoke about observing Earth's energy balance in the era of the Earth System Observatory, a next-generation satellite constellation with tight mission integration and complementary observational capabilities across the mission components that will generate a three-dimensional, holistic view of Earth "from bedrock to atmosphere." He outlined the evolution of the satellite observational record of Earth's energy balance that led to the next generation of observations that is, in part, represented by the upcoming Libera mission—designed to extend the decades-long data record from CERES.[10] Stephens called out observational approaches that offer both greater spatial and spectral information about radiation fluxes than currently available, along with a review of approaches proposed for PREFIRE, the Earth Cloud Aerosol and Radiation Explorer (EarthCARE),[11] and the Atmospheric Observing System (AOS),[12] all planned for launch in the next decade—with EarthCARE planned for 2023.

Maria Hakuba [JPL] continued the theme of future Earth Radiation Budget (ERB) observations—specifically, multiple aspects of ERB research and novel ERB observations. Hakuba reviewed the science goals and objectives of the NASA Libera mission, and discussed different approaches to measuring and estimating EEI, including assessing contemporary sea-level budget using altimetry data and water mass-change observations from the Gravity Recovery and Climate Experiment (GRACE) and GRACE–Follow On missions.[13] She concluded with a novel observing method that measures radiation pressure variations in orbit around Earth.

Peter Pilewskie [LASP—*Libera Principal Investigator*] provided more details about Libera. The mission's attributes enable a seamless extension of the existing long-term ERB climate data record. Libera will acquire integrated radiance over the heritage CERES FM-6 broad spectral bands in the SW and longwave spectral regions as well as total spectra; it also adds a split-SW band to provide deeper insight into SW energy deposition. Libera will also employ a wide field-of-view camera to provide scene context and explore pathways for separating future ERB missions from complex imagers.

The next two presentations focused on the Climate Absolute Radiance and Reflectivity Observatory (CLARREO) mission, the first covering the terrestrial IR portion of the spectrum and the second, the solar near-UV through NIR.

Hank Revercomb [SSEC] led off his presentation by establishing the compelling need for an on-orbit, SI-traceable IR reference sensor that will enable climate change signals to be resolved and assessed much more quickly than current capabilities. The flight of a single, high-quality reference sensor of the type defined for NASA's CLARREO program would enable the international fleet of IR sounders to be intercalibrated and used to establish an initial climate benchmark for future mission comparisons. For the purposes of this discussion, these include CERES and VIIRS on several platforms.

[9] PREFIRE was chosen as one of the two winning proposals in the EVI-4 solicitation. The other winner was the Earth Surface Mineral Dust Source Investigation (EMIT), which is already in operation on board the International Space Station.
[10] Libera was selected as the first Earth Venture Continuity (EVC) mission; it seeks to provide continuity with measurements from CERES. In Roman mythology, Libera is the daughter of the goddess Ceres—an obvious connection with CERES instruments.

[11] EarthCARE is the ESA's Earth Explorer–6 mission—planned for launch in 2023—which will advance understanding of how clouds and aerosols impact terrestrial incoming solar radiation.
[12] AOS will be one of the missions that is part of the Earth System Observatory.
[13] See page 27 of this issue to learn more about the latest GRACE Follow-On Science Team Meeting.

Yolanda Shea [LaRC] followed with an update on the CLARREO Pathfinder (CPF) mission, which is scheduled to begin one year of operations on the International Space Station (ISS) in 2024. CPF will provide a novel view of Earth with its unique combination of measurement capabilities: unprecedented radiometric uncertainty in reflectance, a spectral range of 350–2300 nm, spectral resolution of less than 6 nm, and a spatial sampling resolution of approximately 0.5 km at nadir. These goals will be achieved using a novel approach to on-orbit calibration, as described in the Kopp/Smith summary in Section 6, below. CPF will enable intercalibration of CERES and VIIRS and facilitate a wide range of science applications related to climate benchmarking and attribution, and remote sensing and radiative energy budget applications.

Greg Kopp [LASP] then shifted the discussion to a different type of reference intercalibration as he reviewed ARCSTONE, a 6U CubeSat that is scheduled for launch in 2024 to provide a lunar irradiance reference spectrum in the solar-reflected spectral range to improve calibrations and intercalibrations of almost all in-orbit, Earth-monitoring instruments. The capabilities of the ARCSTONE flight instrument are intended to lower the absolute lunar-irradiance uncertainties from the 5–10% levels derived from Robotic Lunar Observatory (ROLO) models to the 0.5% level for the 350–2300 nm spectral range and incorporate those improvements into the ROLO model.

Susan Breon [GSFC] gave an update on the development of TSIS-2, the follow-on to TSIS-1. TSIS-2 will measure total and spectral solar irradiance. TSIS-2 has two instruments, TIM and SIM, which are being developed by LASP. These instruments—essentially rebuilds of their high-accuracy predecessors on TSIS-1—will provide measurement continuity for the input components of Earth's radiative energy budget, necessary for establishing EEI.

Thomas Sparn [LASP] wrapped up the session with a discussion on lessons learned from implementing Earth system observations and the effect of the global pandemic on future strategies. He discussed the pros and cons of the many past strategies used for solar irradiance measurement capture and the evolution of strategies to ensure data continuity.

Session 6: Improved Solar Reference Spectra: Implications for Remote Sensing and Radiative Transfer

Many applications in remote sensing and radiative transfer require TOA solar reference spectra as a boundary condition. Uncertainties in these spectra can have significant impacts on theoretical and experimental applications, ranging from upper-atmospheric photochemistry to ERB. Presenters in this session focused on new, high-accuracy solar reference spectra along with their use in and effects on remote sensing and radiative transfer data acquisition and analysis.

Odele Coddington [LASP] opened the session with a presentation about a new TSIS-1 Hybrid Solar Reference Spectrum (HSRS). Motivation for the development of the TSIS-1 HSRS came from attempts to resolve differences as large as 8% in solar spectral irradiance observations from the TSIS-1 SIM compared to other commonly used solar reference spectra. Coddington explained the latest extension of the HSRS that now covers a spectral range representing 99.99% of the total solar irradiance. Plans call for adapting the extended TSIS-1 HSRS into a new version of the Naval Research Laboratory solar spectral irradiance (NRLSSI) variability model that is under development.

Daniel Marsh [NCAR] investigated the impacts on the modeled atmospheric state (dynamics and composition) resulting from changing the solar forcing dataset from the current NRLSSI version 2 (NRLSSI2) model to the extended TSIS-1 HSRS using WACCM data. As noted earlier, WACCM is an Earth system model with coupled chemistry that extends from the surface into the lower thermosphere. He noted differences in key constituents in the middle and upper atmosphere such as ozone, hydroxyl, and atomic oxygen, which can be attributed to changes in particular spectral bands.

Greg Kopp filled in for **Paul Smith** [LASP] to discuss how the CPF reflected solar spectrometer will use solar calibrations to obtain low uncertainty in reflectance and reflected radiance. Earth-scene measurements with 0.5-km spatial and 3-nm spectral resolution will achieve an average SI-traceable radiometric uncertainty of 0.3% (1σ) in reflectance by using an on-orbit solar-calibration approach using direct views of the solar disk to obtain the Sun/Earth reflectance ratio. Comparison with the known, SI- traceable solar spectral irradiance, measured by contemporary instruments such as TSIS-SIM, enables conversions to reflected radiances.

Raj Bhatt [LaRC] presented a comprehensive analysis of absolute radiometric comparison between the most widely used SSI datasets and their impacts in satellite sensor cross calibration. Over the past four decades the choice of reference SSI spectrum for satellite data processing has constantly changed due to the increasing availability of more-reliable SSI measurements with extended spectral coverage. Results of his analysis showed that the existing discrepancy in the use of different reference solar spectra in the Level-1B (L1B) processing for the two VIIRS instruments onboard the NOAA-20 and Suomi NPP satellite platforms can result in as much as a 3% radiometric inconsistency in their reflective solar bands radiances.

Group Tours Highlight Unique Archeological Sites and Distinctive Architectural Style in Madison

Symposium participants had their choice of attending one of two tours on the afternoon of May 18: the Effigy Mounds on the University of Wisconsin, Madison (UWM) campus, or the architecture inspired by Frank Lloyd Wright at the Monona Terrace. Short descriptions of both tours follow.

Effigy Mound Tour

Aaron Bird Bear [UWM, School of Education—*Assistant Dean for Student Diversity Program*] gave a tour of the UWM campus—often described as the most archaeologically rich campus in the U.S.

He explained that the UWM campus still has 37 extant effigy and conical linear mounds. These effigy mounds are built only around the western Great Lakes, and nowhere else on Earth. Bird Bear says that they are what makes UWM such a special place, and Madison is at the very epicenter of this ancient indigenous cilvilizaton.

His tour then turned to *Dejope*, a Ho-Chunk Nation word meaning "four lakes." It refers to the area around present-day Madison, which includes UWM. Dejope Residence Hall is where the university now looks to showcase Native American history. Integrated into the floor plan, artwork, and educational areas are the values, symbols, and principles of the First Nation people that called this area home.

To learn more about Native American burial mounds as UWM—including some photos of the mounds—visit ***lakeshorepreserve.wisc.edu/native-americans-and-the-preserve***.

Monona Terrace Tour

The Monona Terrace tour was an opportunity to learn the history of Frank Lloyd Wright's "dream civic center" project for his hometown of Madison—see photo above. Visitors experienced Wright's trademarks of dramatic open spaces, strong geometric forms, and breathtaking views of Lake Monona. This flowing structure shows how Wright saw geometric shapes as underlying forms of nature. This unique site influenced his choice of geometry which is expressed in nearly every aspect of the building.

For more information about both these tours, visit ***mononaterrace.com/experience-monona-terrace/tours-and-education***.

Conclusion

The 2022 Sun–Climate Symposium was remarkable in many ways, but perhaps most noteworthy for being one of the first in-person meetings that many of the participants attended since the start of the global COVID-19 pandemic. Moreover, the last meeting many of them had attended in person was the 2020 Sun–Climate Symposium in Tucson in January 2020—just a little more than a month before our lives changed in dramatic fashion. The organizing committee of this year's Symposium was committed to making this an in-person meeting. Science community constituents were eager to resume in-person meetings, exchange ideas face-to-face, engage in vigorous debate, and enjoy the camaraderie of colleagues over meals. By that measure, the 2022 Sun–Climate Symposium was a resounding success and a wonderful start to the spring-summer meeting period that returned to near normal in 2022.

Plans are already well underway for the next Sun-Climate Symposium, to be held October 16–20, 2023, in Flagstaff, AZ, with the theme *Solar Stellar Variability and its Impacts on Earth and Exoplanets*. Five sessions are planned around different science topics related to the main area. Mark your calendars—abstracts are due by August 7, 2023. Please check the symposium website at ***lasp.colorado.edu/home/meetings/2023-sun-climate-symposium*** for additional details and updates. ■

Summary of the 2022 GRACE Follow-On Science Team Meeting

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Introduction

The 2022 Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (G-FO) Science Team (ST) members met face to face again for their annual gathering after fully virtual meetings in 2020 and 2021. This year 91 participants met October 18–20 at the Helmholtz Centre of the Deutsches GeoForschungsZentrum [(GFZ)—German Research Centre for Geosciences] in Potsdam, Germany—see **Photo**, below. Additionally, 76 participants chose to attend the meeting remotely during the oral sessions. Over the three meeting days, presenters gave 12-minute talks on new results derived from the G-FO observations, as well as the combined GRACE and GRACE-FO [G/G-FO] climate data record, which now spans over 20 years (2002–2022). To date, over 5200 scientific papers have been published using these data, the equivalent of about five new publications every week—which places G/G-FO amongst the most prolific and productive Earth Science missions. Throughout the meeting, presenters highlighted the unique value of this nearly uninterrupted long-term record—which G-FO is now extending into its third decade.

As has been customary, the meeting opened with a G-FO project status session addressing mission and flight segment technical status, future science plans, and updates on the latest data release from the Science Data System (SDS) centers.

The following eight sessions consisted of over 60 analysis, algorithm, and science presentations contributed by ST members and other attendees. The full meeting program included 85 oral and 17 poster presentations. Proceedings and presentations are available online at ***meetingorganizer.copernicus.org/gstm2022/presentations***. The meeting abstracts were used to compile the following summary, which starts with a G-FO mission status update, followed by 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. G-FO is a U.S.–German collaboration between NASA and GFZ.

As of December 2022 the G-FO project team has processed and released 51 monthly gravity fields—the most recent for November 2022 (at the time of 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 operates the Laser-Ranging Interferometer (LRI)—a novel technology demonstration—to generate more accurate satellite-to-satellite ranging observations for future GRACE-like missions. The LRI has been successfully operating in parallel with MWI throughout the mission. The LRI continues to return excellent quality data and has proven operationally to be very stable and reliable. G-FO is in its

Photo. Group picture of the 2022 GRACE-FO Science Team Meeting attendees. **Photo credit:** GFZ primary mission science operations phase, which will last through May 2023, i.e., five years after launch. The project team will submit a NASA Senior Review proposal in the spring of 2023 to extend mission operations through 2026. NASA and the GFZ have already signed a Memorandum of Understanding to continue their cooperation on G-FO through the end of 2026.

Programmatic, Mission, and Operations Updates

The first meeting day began with opening remarks from the German Project Manager Professor **Frank Flechtner** [GFZ], followed by detailed assessments of G-FO mission and operations status from the core SDS centers and flight operations teams. The day concluded with an Open Forum, which was a welcome opportunity for colleagues to discuss details related to the G/G-FO missions and to simply enjoy being able to interact with one another in person after COVID necessitated virtual-only meetings for so long.

GRACE Follow-On and GRACE Project Status

Felix Landerer [NASA/Jet Propulsion Laboratory (JPL)—*G-FO Project Scientist*] 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.

The overall G-FO science instrument and flight system performance during the mission have been stable, and monthly mass-change data have been delivered to users ahead of schedule (on average, within 42 days instead of the 60-day requirement). Landerer highlighted that the G-FO SDS team released an improved, reprocessed accelerometer calibration in summer 2022 to correct a small seasonal bias that the ST has identified in the mass-change data record for some regions, e.g., over Antarctica and the Arctic. The SDS team continues to focus on improving data calibration for the accelerometer measurements on one of the two G-FO spacecraft—which are noise contaminated. This will be even more important as the current Solar Cycle 25 will gain strength throughout 2023 and 2024, which means that higher nongravitational forces will be acting on the satellites that will need to be properly accounted for in the science data processing.[1]

Landerer also highlighted the growing contributions of the G/G-FO data record for Essential Climate Variables (ECVs) in the Global Climate Observing System (GCOS). In addition to the existing ECV contributions of G/G-FO data to ice sheet and glacier mass changes, sea level, and groundwater, the recently updated ECV inventory (version 4.1),[2] now contains—for the first time—a *Terrestrial Water Storage* (TWS) data product, for which the long-term G/G-FO data record is the core observation contribution. Landerer highlighted that "Earth's climate system has been doing rather strange things" lately, as precipitation anomalies deviated significantly from climatic averages in 2021 and 2022: severe precipitation deficits in the Southwest U.S. and Western Europe have led to significant reductions in land water storage and drought issues, while precipitation surpluses around the U.S. Great Lakes, Western Australia, and Lake Victoria (South Australia) made these regions more prone to flooding. Meanwhile, ice melt from Greenland and Antarctica has continued unabated, with both ice sheets having lost approximately 7000 gigatons of ice since 2002—and raised global sea levels by 22 mm (~0.9 in). The unique G/G-FO data record continues to enable novel and impactful advances in the understanding of Earth system mass transport dynamics, and helps scientists better map out the future of water availability and sea level rise.

Following the opening presentation, a series of status reports on programmatic G-FO mission operations, science operations, and SDS processing took place.

Krzysztof Snopek [GFZ] reported on 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 the GSOC.

Himanshu Save [University of Texas, Center for Space Research (CSR)] provided the science operations assessment. He described the project team's approach to actively managing the G-FO satellites' orbits by performing incremental altitude increases to mitigate prolonged orbit repeats with poor ground track coverage and reduce atmospheric drag on the satellites for better science performance.

Christopher McCullough [JPL] reviewed the status of G/G-FO Level-1 (L1) data reprocessing at JPL, detailing the improvements made in the accelerometer calibrations. The team managed to use the noisy accelerometer data (discussed earlier) on one satellite and extract valuable science information for improved data retrievals.

Samuel Francis [JPL] provided a status update of the experimental LRI performance and its highly precise ranging measurements—which provide as much as 30 times more-accurate satellite-to-satellite ranging

[1] The Sun cycles through an approximately 11-year cycle of activity. The solar maximum (point of maximum Solar activity) for Solar Cycle 25 is expected sometime between now and 2026. Increased solar activity can place a strain on satellites in space from increased radiation pressure, solar winds, and the like.

[2] The ECV inventory can be found at ***gcos.wmo.int/en/essential-climate-variables***.

than the MWI. The in-orbit LRI experience has been very positive: LRI is collecting science data in parallel with MWI and operating largely autonomously. In 2022 the team successfully uploaded a software update that further improves the already excellent quality of LRI data.

G-FO and GRACE Data Product Updates

After these three presentations, representatives of the three G-FO mission SDS centers (JPL, GFZ, and CSR) summarized the status of the latest Release of the G-FO Level-2 gravity field and mass change data products (RL06.1), including an overview of background dealiasing models and the GravIS portal (GFZ),[3] the updated JPL mascon[4] data product (JPL), and new data-processing strategies, e.g., via range acceleration (CSR), alternative single instrument processing unit processing (GFZ), and using the novel LRI ranging observations (JPL, CSR, GFZ). The GRACE team provided an update on the final release of the 2002–2017 GRACE data processing (G-RL07). While initially slated for a 2022 release, the team now targets release early in 2023.

Open Forum

Following the project team's status presentations, a two-hour Open Forum session took place that provided an interactive, open floor environment to discuss in more detail the mission's performance and near-term operations plans, and to answer questions and discuss suggestions from the community. The forum also provided a welcome opportunity for early-career scientists to interact with the project team and research groups and become more familiar with operational and calibration procedures and their impact on science data quality. The forum was well received by meeting attendees, probably because the virtual-only meetings of the last two years lacked opportunities for more informal exchanges.

Science Presentations

The open-submission science sessions centered around different thematic topics, including G/G-FO analysis techniques and mission studies for future gravity mission concepts (covered in a separate section in this summary); and science analysis of mass-transport data in the fields of hydrology, oceanography, glaciology, and solid-Earth physics.

A cross-cutting theme that emerged during the meeting was the growing value of interdisciplinary and multi-instrument analysis that utilizes 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* sensor-combinations can yield improved spatial and temporal resolutions that enable advances in understanding Earth system processes. Additionally, several of the presentations—particularly in the hydrology session—featured results (e.g., groundwater monitoring) that advance applications science results from G/G-FO in the broader context of NASA's Applied Sciences Program.

Analysis Techniques and Intercomparisons

With 38 abstract submissions, this session was the largest of the meeting. Presentations included several by the SDS centers and ST members highlighting progress in instrument data calibrations, and some using the more than four years of G-FO data that have been collected to compare intersatellite range spatiotemporal acceleration signals derived from MWI and the technology-demonstration LRI. Several teams presented advances in LRI data calibrations that are useful for instrument characterization and relevant for advancing the development of stand-alone LRI instruments for upcoming missions.

There were also several presentations on deriving submonthly mass change information from G-FO data. Whereas with traditional techniques, sufficient global coverage requires accumulating data over a full month, advanced algorithms have been developed to derive 10-day or even 5-day mass change data grids. One advantage of these approaches is reduced latency of a few days (*versus* up to 40 days for monthly data grids), which make the data more useful for monitoring applications, e.g., flood detection. These approaches can also benefit from the significantly lower noise level in LRI data compared to MWI.

Representatives from G/G-FO processing centers[5] presented updated gravity-field time-series data, which capitalize on improved parameterizations and background models (e.g., for tides) for improved retrievals. The upcoming final GRACE data release (RL07) will incorporate better characterization of individual instrument measurement errors (e.g., from star cameras, accelerometers, or ranging instruments), which in turn yield improvements in mass change maps and quantifying data uncertainties. Several groups in the U.S., Australia, and Europe have developed advanced mass change data retrievals that support increasingly application focused projects e.g., the European Union's Horizon 2020 project, Global Gravity-based Groundwater Product (G3P).

[3] Via its web portal GFZ's GravIS (***gravis.gfz-potsdam.de***) provides user-friendly mass-change products based on G/G-FO data that are tailored for applications in the fields of hydrology, oceanography, and cryosphere.

[4] A mascon, or mass concentration block, is a form of gravity field basis function to which G/G-FO's intersatellite ranging observations are fit. Learn more at ***go.nasa.gov/2M9d2gx***.

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

There was a presentation on how G/G-FO data products make use of ground-based geodetic observations, e.g., satellite laser-ranging (SLR) via a network of dedicated SLR satellites. Conversely, SLR data processing can be improved by incorporating G/G-FO observations to better account for long-term and seasonal mass transport in the Earth system. These advances translate to improvement in geodetic applications beyond the dedicated G/G-FO missions.

Hydrology

This session had 19 presentations highlighting novel hydrology research and applications using G/G-FO data. In several presentations the unique value of long, uninterrupted mass change climate data record came into focus. Continuing a trend from the last few years, research that combines data from G/G-FO with data from other satellite or ground-based sources, as well as *model-data fusion*—where observations from G/G-FO and other satellites are combined with output from hydrological models—has led to new insights and data product innovations for research and applications.

Another presentation focused on using G/G-FO data for drought monitoring in Europe. There have been several years recently (e.g., 2002, 2018–2019) with below average precipitation and above normal temperatures across much of Europe. Accompanying the drier and warmer than average weather is an associated decrease in lake and groundwater levels, decreased flow in surface rivers and streams, damage to forest ecosystems, and reduced or failing crop yields in agriculture. These highly visible impacts of prolonged drought have raised public concern in Europe about the current and future availability of water resources. The presenter showed how G/G-FO data played a key role in discerning the full scope of the European drought as it increasingly impacts deeper groundwater systems.

There was also a report about analysis G/G-FO signatures of human intervention in the water cycle for the East-African Rift Region, where managed water storage in Lake Victoria has led to a measurable increase in water storage in and around the lake.

Another study examined signals over the Grand Ethiopian Renaissance Dam [about 45 km (28 mi) east of the border with Sudan] during its initial filling stages (2020–2021). The study found apparent discrepancies between water level observations (e.g., through analysis of EU Copernicus Sentinel-1 satellite data), and G/G-FO total water mass data. One plausible mechanism could be water losses due to infiltration along the highly fractured faults and shear zones in this area and within the weathered basement rocks. Further research on this topic will focus on assessing these possible sinks for water.

A team from the Middle East has quantified how the 20-year G/G-FO data record provides a basis to assess how engineered and nonengineered river basins might respond to water cycle variability. Essentially, land water accumulation over nonengineered basins (e.g., those that lack managed dams, reservoirs) featured significantly faster water decline as excess water drained or evaporated over a few months. This suggests that highly engineered watersheds may be better prepared to deal with the projected increase in the frequency and intensity of extreme rainfall and drought in the twenty-first century.

Another team focused on how G/G-FO data can be used to improve seasonal forecasts of land water storage. Currently, meteorological seasonal forecasts have large uncertainties—which inevitably map into highly uncertain land water storage predictions. Based on the 20-year G/G-FO data record, statistical linkages with hydrometeorological variables (e.g., precipitation, sea surface temperature, or runoff) can be used to improve land water storage forecasts by up to one year—an improvement on existing approaches.

Another presentation showed how, on time scales of multiple years to decades, G/G-FO data provide crucial measurements that would otherwise be missed and therefore provide challenges to using global hydrological computer models for predicting the evolution of water resources in changing climate conditions. For example, slow changes in the terrestrial water cycle may be overlooked in models due to inaccurate meteorological forcing (e.g., precipitation), unresolved groundwater processes, anthropogenic influences, changing vegetation cover, and limited calibration/validation datasets.

Despite these shortcomings in some hydrology models, global coupled climate models play an important role in predicting future climate conditions. The 20-year G/G-FO land water storage data record provides a key dataset to validate models. An evaluation of a large ensemble of Coupled Model Intercomparison Project Phase 6 (CMIP6) models revealed some long-term wetting and drying conditions in TWS over hotspot regions, in common with trends in G/G-FO observations. Long-term wetting and drying conditions predicted by global climate models are often confirmed by the 20-yr G/G-FO data, including drying trends over much of southwestern North America and the Mediterranean region.

A number of presentations focused on identifying long-term trends in the water cycle, and their impact on water storage over land. Strong signatures of interannual variability—e.g., from global El Niño/La Niña events in 2010–2011/2015–2016—are evident in the G/G-FO data, making it a challenge to disentangle the El Niño Southern Oscillation (ENSO) signal from anthropogenic climate trends. As other presenters highlighted, it is especially important to continue the G/G-FO-like (i.e., Mass Change) observations through the next 10–20 years without interruption to make progress in disentangling climate variability from secular change over key land hydrology regions. (See the next section on *Next-Generation Gravity Mission Concepts* on page 33, to see what is envisioned.)

Several presenters discussed using G/G-FO data to advance hydrologic modeling for forecasting and climate predictions. Using a water balance approach, G/G-FO data show that increased evapotranspiration occurs during droughts—but that Earth System climate models tend to underestimate this probability by nearly half, primarily due to missing representations of soil structure effects on soil evaporation and incorrectly parametrized plant and soil traits. Therefore, continued G/G-FO observations can play a key role in improving these computer models and help to reduce uncertainties in the water–energy–food nexus.

Multiple projects now successfully assimilate G/G-FO data into land surface models in order to constrain the terrestrial water storage state variables (e.g., groundwater, soil moisture, snow) in those models, and to generate weekly global drought and wetness indicators. In regions of steep terrain or highly heterogeneous hydrological conditions (e.g., mountainous terrain), innovative new G/G-FO products and/or data assimilation schemes are needed to overcome issues associated with coarse spatial resolution, such as correctly simulating snow levels in mountainous regions like the Colorado River Basin in the U.S.

G/G-FO provides unique information on the wetness state of a river basin with regard to its flood-generating potential. There was a report on progress in generating a low-latency, five-day average G/G-FO field that may be useful to detect and predict hydroclimate events (e.g., flooding) to infer and understand rapid global and local geophysical processes. To further enhance the accuracy of the observations, a probabilistic deep-learning model that used precipitation and air temperature as predictors showed promise in providing a skillful operational data product for applications.

Cryosphere

Three dedicated contributions in this session reported on new ice mass balance results for Earth's land ice, as well as on novel data combination approaches that can improve spatial resolution over that from G/G-FO-only data.

Over the 20-year G/G-FO record, Greenland has experienced a persistent mass loss at 251 Gt/yr, with an acceleration of an additional 3 Gt/yr/yr, and large summer loss events (400–600 Gt) in 2012, 2017, and 2019. The mass balance regime has been evolving significantly in recent years, especially over northern Greenland—which holds the largest potential for rapid sea level rise.

In Antarctica, ongoing mass losses in the Amundsen Sea Embayment of West Antarctica (122 Gt/yr), Antarctic Peninsula (26 Gt/yr), and Wilkes Land in East Antarctica (33 Gt/yr) dominate a small but significant increase (47 Gt/yr since 2009) in snowfall in the Queen Maud Land sector of East Antarctica.

The remaining glaciers and ice caps lost an average of 274 Gt/yr, with an acceleration of 4 Gt/yr/yr. Overall, the Northern Hemisphere (NH) is losing much more ice mass than the Southern Hemisphere (SH). The largest NH contributors are in the Arctic: the Canadian Archipelago (70 Gt/yr), Alaska (72 Gt/yr), the Russian Arctic (21 Gt/yr), the Svalbard (a.k.a., Spitsbergen) archipelago, and Iceland (29 Gt/yr). High Mountain Asia averages 22 Gt/yr mass loss—but with a large interannual variability. By comparison, the largest single SH contributor is Patagonia (35 Gt/yr).

Another presentation focused on a study that combined gravity and ice-height satellite observations to improve the spatial resolution of the resulting ice mass balance estimate. Mass change observations from G/G-FO have limited spatial resolution of 300 km, but accurately measure mass changes of ice sheets and glaciers. Changes in ice heights can be accurately measured with altimetry satellites (e.g., NASA's Ice, Clouds, and land Elevation Satellite–2 (ICESat-2) and the European Space Agency's (ESA) CryoSat-2), which have a very fine spatial resolution (less than 10 km) but are not directly sensitive to the density (and thus mass) of the changing ice volumes. The advantages of combining both data types (i.e., direct sensitivity to mass change from G/G-FO complemented with high-spatial-resolution altimetry) improve the spatial resolution of mass balance estimates across Greenland and Antarctica and provide gain-improved process understanding at the ice-stream level.

Solid Earth Sciences

Two presentations in this area evaluated signals in the G/G-FO data record associated with the large Tohoku (Japan, 2011) and Maule (Chile, 2010) earthquakes—see **Figure 1** on page 32. While large mass shifts and associated gravity signals during and after the earthquakes have been well documented, newer research has focused on possible precursor signals in the G/G-FO data. For both the Tohoku and Maule events, researchers found signals in the G/G-FO data records that suggest deep subduction zone activity several weeks and even months prior to the destructive quakes. Satellite observations of Earth's time-varying gravity field detect slow, deep, mass redistributions along major plate boundaries and provide novel insights into dynamic processes in the subduction system. These data are essential to better understand the seismic cycle and could potentially lead to improvements in early earthquake warning.

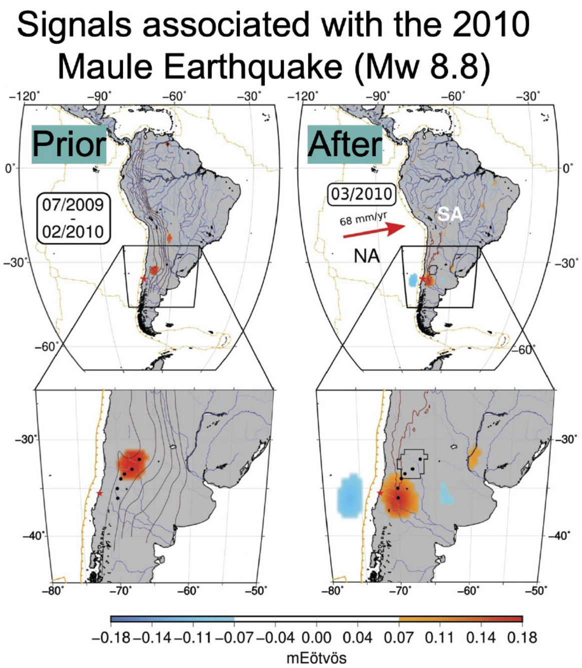

Figure 1. An anomalous gravity gradient signal has been detected prior to the Maule earthquake in Chile (2010) in GRACE satellite data (orange area, *left* panels—bottom panel is a close-up of the top image). This signal is consistent with extensional deformation of the subducted slab near 150 km (~93 mi) depth along the Nazca Plate subduction direction—associated with large-scale fluid release. The magnitude 8.8 earthquake that occurred on February 27, 2010, may have originated from the propagation up to the trench of this deeper slab deformation. Note that a large gravity signal is also apparent after the quake [*right* panels] although in a different location. **Figure credit:** Marie Bouih/University of Paris, Institut de Physique du Globe de Paris (IPGP) [Paris Institute of Planetary Physics], from a paper published in *Earth and Planetary Science Letters* (***doi.org/10.1016/j.epsl.2022.117465***)

Oceanography

In the Oceanography session, presenters reported on the combination of data from 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 heat changes. There was a suggestion that global sea level budget—the contributions of combined density and mass-changes to sea level—is impacted by errors in Argo salinity sensors and a possible drift in the altimeter's radiometer instruments—see **Figure 2**, above right. Despite these issues, the sea level budget approach (using all three observing systems) was successfully used to identify mass flux into the Gulf of Mexico and warming-driven redistribution of mass onto its shelf areas, explain a dominant fraction of coastal sea level trends observed at tide gauge stations throughout the Gulf, particularly along the west Florida shelf. The

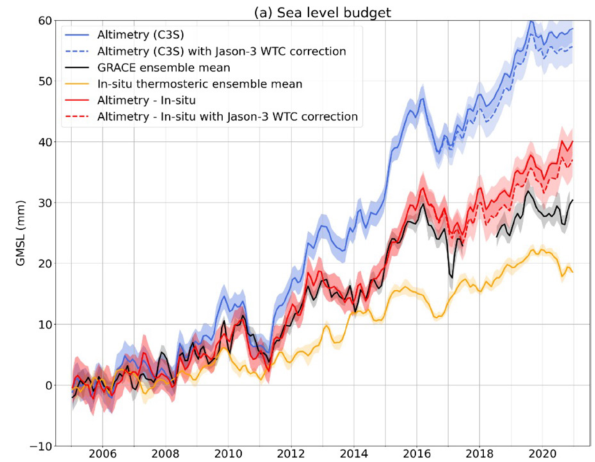

Figure 2. Global mean sea level change (*blue*, measured with satellite altimeters) is the sum of ocean mass changes (*black*, from G/G-FO) and from ocean thermal expansion (*yellow*, measured with ocean profiling Argo floats). The agreement between black and red lines provides a measure of the quality and closure of the observing systems. Starting about 2016 a gap appears, which has been attributed to possible further altimeter corrections, as well as Argo sampling biases. The GRACE-to-GRACE-FO transition from 2017–2018 has been found to be bias-free. **Figure credit:** Anne Barnoud/Magellium, *France*, from a preprint of a paper posted on *EGUSphere*—the EGU's interactive community forum (***doi.org/10.5194/egusphere-2022-716***)

results highlight the ability of ocean-bottom pressure measurements from G/G-FO to capture the spatially varying redistribution of mass driven by oceanic uptake of heat.

To further advance the study of ocean dynamics, a preliminary novel G/G-FO dataset of ocean bottom pressure was presented that yields improvement by comparison with ocean bottom pressure recorders, tide gauges, and ocean state estimates. Similarly, advances in ocean model simulations to improve the G/G-FO data retrievals will be incorporated in the upcoming RL07 data releases to better correct for transient effects of high-frequency (i.e., hourly-to-monthly) atmosphere–ocean mass variability that would otherwise alias into monthly-mean global gravity fields. High-resolution ocean simulations revealed that chaotic ocean-eddy effects generate mass change signals detected by G/G-FO and need to be considered when interpreting G/G-FO-derived ocean dynamic processes.

Multidisciplinary Science, Applications, and Data Services

While gravity and mass changes are the primary focus of the G-FO mission, the two satellites at their relatively low orbit altitude of 490 km also pick up signals of opportunity that can provide a novel view of Earth system processes and events. One team reported on observing the global ionospheric disturbance after the Hunga Tonga–Hunga Ha'apai (HT-HH) volcanic eruption on January 15, 2022. These unique observations can be used to study less-known high-altitude ionospheric processes. In addition to the gravity measurements, G-FO provides Global Positioning System–Radio Occultation (GPS-RO) data products used in weather and climate applications—similar to what was done with GRACE GPS-RO data. After several onboard software updates and raw data reader improvements since March 2020, rising occultations from the lead G-FO satellite (GF1)—and since September 2021 setting occultations from the trailing G-FO satellite (GF2)—are continuously available. Both satellites provide about 400 near-real-time atmospheric profiles daily for use by weather service centers.

Other presentations in these sessions assessed:

- The impact of land water storage changes in so-called polar motion excitation at subseasonal time scales;
- A six-year mass variability cycle in the climate system that might be linked to deep solid-Earth processes; and
- The combination of G/G-FO data with other satellites' observations (e.g., altimetry, high-resolution visible glacier imagery) to reduce spatial uncertainties in G/G-FO data.

The NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) team, based at JPL, presented an updated plan to migrate all G/G-FO data products to the NASA Earthdata Cloud by early 2023 The colocation of data storage, tools, and services allows easy access to data and analysis capabilities in the cloud for a more flexible and scalable approach to working with large datasets, programs, and operating systems.

In addition to cloud-based data services from the PO.DAAC, ST members are releasing open-source software tools to perform various analytical tasks, such as computing the gravity field from satellite and terrestrial data, and calculating basin-averaged total water storage anomalies to assess water deficits.

Next-Generation, Gravity-Mission Concepts

The Next-Generation-Gravity-Mission (NGGM) session explored future instrument developments and mission concepts. This discussion included concepts from NASA and the Deutsches Zentrum für Luft- und Raumfahrt [(DLR)—German Aerospace Center], as detailed below.

NASA: Mass Change Designated Observable and DLR/NASA: GRACE-I

The 2017 National Academy of Sciences' Decadal Survey for Earth Science and Applications from Space highlighted mass-transport monitoring through gravity change (Mass Change, or MC) as one of five *designated observables* (i.e., top priorities for study) in Earth observations for the next decade, in collaboration with international partners.[6] Since then, the NASA MC Designated Observable study was concluded in 2021. Thereafter, NASA directed JPL to initiate the Mass Change Project,[7] which developed a suitable MC mission concept in its Pre-Phase A mission formulation stage, and successfully passed the NASA/JPL Mission Concept Review in June 2022. The baseline architecture is a partnership between NASA and DLR with an architecture building upon the heritage of G/G-FO. This concept meets the primary goal of maintaining continuity in the mass change data record, within NASA budgetary constraints.

On the DLR side, a similar concept is known as GRACE-ICARUS,[8] hereinafter referred to as "GRACE-I" Following a Phase 0 study in 2021, GFZ reported on the status of their Phase A work (from April to September 2022), which had significant support of NASA—and JPL in particular—building on the very successful U.S.–German G/G-FO technological and scientific partnership.

The MC/GRACE-I mission (a final name will be chosen later) will be a single satellite pair based on a fully redundant LRI in polar orbit at an altitude of 500 km (~311 mi). In order to avoid a data gap between G-FO and MC/GRACE-I, an MC/GRACE-I launch date of no later than 2028 is highly desirable. It would be the first component of a more capable constellation of other mass change satellite missions to provide gapless, long-term observations of this important climate variable, with increased spatiotemporal resolution.

In parallel with these efforts at NASA and DLR, ESA is continuing Phase-A studies focused on a second pair of satellites to complement the NASA/DLR MC/GRACE-I mission. The second pair from ESA would fly in an inclined, offset orbit (i.e., not polar, but near 70° inclination, and in this way enhance spatial and temporal resolution and, consequently, the overall science and applications value of the combined two-pair observing system.

Maturation of the G-FO–LRI Technology Demonstration

The technology demonstration LRI on G-FO continues to surpass performance requirements: It autonomously maintains its intersatellite laser link and performs without any issues. For the MC/GRACE-I mission, the

[6] For an overview of the 2017 Earth Science Decadal Survey visit ***go.nasa.gov/2wXJn2n***. The full report can be accessed in several forms from ***nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth***.

[7] Mass Change is one of the missions (areas of focus) planned as part of the Earth System Observatory. Learn more about the Earth System Observatory at ***go.nasa.gov/3wmt4pm***.

[8] ICARUS stands for International Cooperation for Animal Research Using Space.

LRI-only technology will replace MWI as the primary science instrument to continuously measure intersatellite ranging variations. The LRI team presented progress on efforts to take the LRI from the technology demonstration level to prime instrument rating, incorporating lessons learned on G-FO as well as new developments based on ground testing. In particular, the team is focusing on developing and improving techniques to accurately determine the LRI's absolute laser frequency in orbit. This is important because the current G-FO approach of correlating MWI and LRI range measurements cannot be used for future missions that use the LRI as the primary ranging measurement system.

Other Instrument and Gravity Mission Concept Updates

A consortium consisting of the University of Florida, JPL, Ball Aerospace, and Embry–Riddle Aeronautical University—with funding from the NASA Earth Science Technology Office (ESTO)—reported on their collaborative development of a Simplified Gravitational Reference Sensor (S-GRS). The S-GRS is an ultraprecise inertial sensor—estimated to be at least 40 times more sensitive than the GRACE accelerometers—to measure nongravitational accelerations on the spacecraft with high accuracy. Such an increase in performance allows future missions to take full advantage of the high accuracy of the GFO-LRI ranging systems to retrieve mass change observations.

There were also reports on progress on the developing low-frequency optomechanical accelerometers for geodetic applications. These compact, portable, cost-effective, and high-sensitivity optomechanical inertial sensors build upon recent advances in small form factor optomechanics to measure accelerations needed for eventual integration into satellites.

The presentations on instruments and mission concepts was complemented by a number of observing system simulations that explored how future mass change observations can be improved by additional measurements (e.g., from other low-Earth-orbiting satellites), and how different observing system architectures resolve and decouple natural and anthropogenic climate forcing mechanisms to better inform and validate global climate models.

Summary

The hybrid G-FO STM 2022, having brought together over 160 international participants, once again highlighted the broad range of science results and applications that are supported and uniquely enabled by satellite gravimetry-based mass change observations. The G-FO data, available since June 2018 and now spanning over four and a half years continues to prove vital to understanding Earth's changing hydrosphere, including sea level, ocean currents, and water distribution over land. Together, 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 GRACE-FO project team is focusing on providing the mass-change data record at a level of performance consistent with that of GRACE. As Solar Cycle 25 moves toward its maximum, these efforts include occasional orbit maintenance maneuvers and dedicated calibration campaigns for the mission's accelerometer instruments. The novel LRI technology on G-FO has been a great success—and will be used as the primary satellite ranging science instrument in the next Mass Change mission.

As the world emerges from the COVID pandemic, the multinational mission and science operations team—composed of members of JPL, GFZ, CSR, and GSOC, together with industry support—continues to work efficiently and successfully to ensure continuity of the long-term gravity and mass change data record.

The next GSTM will be held in October 2023 in the U.S., organized by JPL. Updates will be posted at ***grace.jpl.nasa.gov*** as it becomes available. ■

NASA Enables Future of Science Observation through Tri-Band Antennas

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

NASA's Near Space Network[1] enables spacecraft exploring the solar system and Earth to send back essential science data for researchers and scientists to investigate and make profound discoveries. Now, the network has integrated four new global antennas to further support science and exploration missions. In December 2022 antennas in Fairbanks, AK, Wallops Island, VA, Punta Arenas, Chile, and Svalbard, Norway went online to provide present and future missions with S-, X-, and K_a-band communications capabilities.

These new antennas—see **Photos 1 and 2**, below—were created to support missions capturing immense amounts of data. Just as scientists increase their instrument capabilities, NASA also advances its communications systems to enable missions near-Earth and in deep space.

[1] NASA's Near Space Network fulfills the essential needs of user missions, empowering them with mission-critical communications and navigation services and enabling the transmission of science and exploration data to and from space. As a single point of service for missions in the near-space region—out to two million kilometers away—the network connects users with either government or commercial service providers. More information can be found at ***esc.gsfc.nasa.gov/projects/NSN***.

This antenna upgrade is bringing unprecedented flexibility to the Near Space Network and will enhance *direct-to-Earth communications*—the process by which a satellite takes a picture and then sends the image over radio waves to an antenna on Earth. The data are then processed and sent to scientists.

The Near Space Network is managed by NASA's Space Communications and Navigation (SCaN) program office, which oversees development and enhancement of NASA's two primary communications networks: the Near Space and Deep Space networks.[2]

The Near Space Network provides missions with communications services through a blend of government-owned and commercial assets. To develop these new antennas, the team worked with commercial partner Kongsberg Satellite Services (KSAT), who created the Chile and Norway antennas, while NASA developed the other two in Virginia and Alaska.

Now operational, the four antennas are integrated into the network's service catalog, advancing its capabilities to support science and exploration missions that use enhanced instrumentation. Now, missions using

[2] More information about NASA's Space Communications and Navigation (SCaN) program office can be found at ***go.nasa.gov/40GNZSN***.

Photo 1. [*Left*] NASA's new tri-band antenna in Fairbanks, AK. **Photo credit:** NASA. **Photo 2.** KSAT antenna in Svalbard, Norway, with its radome fully installed. The radome is a dome-shaped enclosure that protects a radar antenna and electronic equipment from weather. The radome is constructed of material transparent to radio waves. **Photo credit:** KSAT

Figure. Rendering of NASA's Plankton, Aerosol, Clouds, ocean Ecosystem (PACE) satellite on orbit. PACE is scheduled to launch in 2024.
Figure credit: NASA

the network will be able to send back terabytes of data for processing and discovery. An example is the upcoming Plankton, Aerosol, Clouds, ocean Ecosystem (PACE)[3] mission (scheduled to launch in 2024) which will help researchers better understand ocean ecosystems and carbon cycling and reveal how aerosols might fuel phytoplankton growth on the ocean's surface—see **Figure**.

"Missions like the PACE satellite incorporate high-resolution science instruments," said **Damaris Guevara** [NASA's Goddard Space Flight Center—*Networking Upgrade Project Lead*]. "These instruments require advanced space communications capabilities, like K_a-band, to get the entirety of their data back to Earth."

The new antennas also will have new networking capabilities. All four ground stations are incorporating Delay/Disruption Tolerant Networking (DTN).[4] DTN will empower missions with unparalleled connectivity by storing and forwarding data at points along the network to ensure critical information reaches its destination. DTN is an advanced communications capability being developed and tested by NASA's SCaN and Space Technology Mission Directorate (STMD).[5]

Additionally, to enhance mission teams' access to data, the network incorporates cloud-based data storage services. Satellites like PACE will downlink their data to an antenna, and that data will go through the ground station's high-rate data processors to a cloud-based storage and data access service that will allow mission teams to acquire their data faster and from almost anywhere. This reduces hardware needs and lowers overall storage costs.

Multiple missions will benefit from this new infrastructure and advanced capabilities, including the NASA-Indian Space Research Organisation Synthetic Aperture Radar (NISAR)[6] satellite. Launching in 2024, NISAR will measure Earth's changing ecosystems, dynamic surfaces, ice masses, and more.

With four new antennas around the globe, the Near Space Network is advancing its capabilities to support science and exploration missions that use enhanced instrumentation. Now, missions using the network will be able to send back terabytes of data for processing and discovery. ■

[3] More information about PACE can be found at ***pace.gsfc.nasa.gov***.
[4] More information about DTN can be found at ***go.nasa.gov/3TXJvFh***.
[5] More information about STMD can be found at ***nasa.gov/directorates/spacetech/home/index.html***.

[6] More information about NISAR can be found at ***nisar.jpl.nasa.gov***.

NASA Says 2022 Fifth Warmest Year on Record, Warming Trend Continues

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

Earth's average surface temperature in 2022 tied with 2015 as the fifth warmest on record, according to an analysis by NASA. Continuing the planet's long-term warming trend, global temperatures in 2022 were 1.6 °F (0.89 °C) above the average for NASA's baseline period (1951–1980), scientists from NASA's Goddard Institute for Space Studies (GISS) in New York reported.[1]

"This warming trend is alarming," said NASA Administrator **Bill Nelson**. "Our warming climate is already making a mark: Forest fires are intensifying; hurricanes are getting stronger; droughts are wreaking havoc, and sea levels are rising. NASA is deepening our commitment to do our part in addressing climate change. Our Earth System Observatory[2] will provide state-of-the-art data to support our climate modeling, analysis, and predictions to help humanity confront our planet's changing climate."

The past nine years have been the warmest years since modern recordkeeping began in 1880. This means Earth in 2022 was about 2 °F (or about 1.11 °C) warmer than the late 19th century average. "The reason for the warming trend is that human activities continue to pump enormous amounts of greenhouse gases into

[1] NASA uses the period from 1951–1980 as a baseline to understand how global temperatures change over time. That baseline includes climate patterns such as La Niña and El Niño, as well as unusually hot or cold years due to other factors, ensuring it encompasses natural variations in Earth's temperature.

[2] More information about NASA's Earth System Observatory can be found at ***science.nasa.gov/earth-science/earth-system-observatory***.

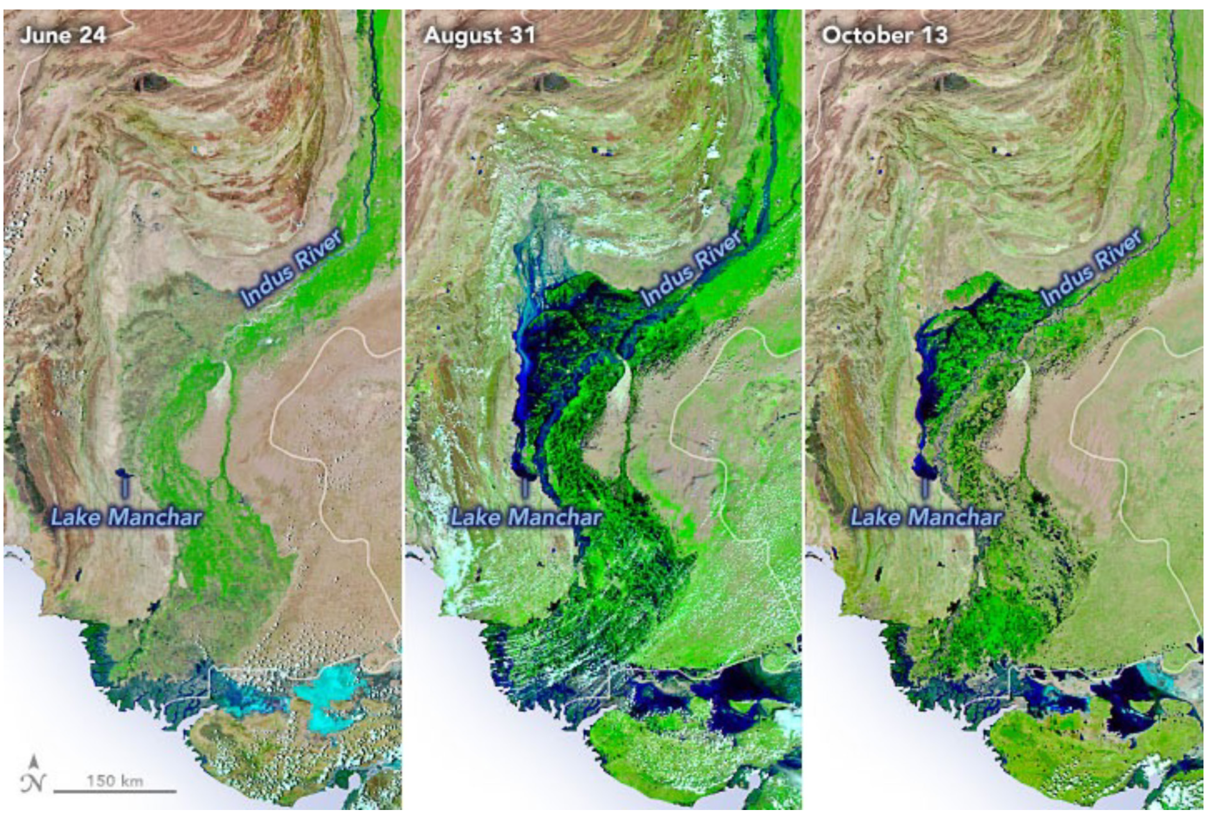

Figure. The images show the progression of flooding from torrential monsoon rains that devastated Pakistan in 2022. Sindh province is shown on August 31, 2022, near the peak of the flooding [*center*]. By October 13, 2022, a considerable amount of water had drained off the landscape and back into rivers [*right*]. But many areas remained wet and waterlogged in comparison to June 2022 [*left*]. All three false-color images were acquired by the Visible Infrared Imaging Radiometer Suite (VIIRS) on the NOAA-20 satellite and are based on VIIRS observations of short-wave infrared and visible light—a combination that makes it easier to distinguish between water (blue) and land (green). **Image credit:** NASA's Earth Observatory the atmosphere, and the long-term planetary impacts will also continue," said **Gavin Schmidt** [GISS—*Director*]—NASA's leading center for climate modeling.

Human-driven greenhouse gas emissions have rebounded following a short-lived dip in 2020 due to the COVID-19 pandemic. Recently, NASA scientists, as well as international scientists, determined carbon dioxide emissions were the highest on record in 2022. NASA also identified some super-emitters of methane—another powerful greenhouse gas—using the Earth Surface Mineral Dust Source Investigation (EMIT)[3] instrument that launched to the International Space Station last year.

The Arctic region continues to experience the strongest warming trends—close to four times the global average—according to GISS research presented at the 2022 annual meeting of the American Geophysical Union,[4] as well as a separate study published by *Nature* in August 2022.[5]

Communities around the world are experiencing impacts scientists see as connected to the warming atmosphere and ocean. Climate change has intensified rainfall and tropical storms, deepened the severity of droughts, and increased the impact of storm surges. Last year brought torrential monsoon rains that devastated Pakistan—see **Figure** on page 37—and a persistent megadrought in the U.S. Southwest. In September, Hurricane Ian became one of the strongest and costliest hurricanes to strike the continental U.S.

Tracking Our Changing Planet

NASA's global temperature analysis is drawn from data collected by weather stations and Antarctic research stations, as well as instruments mounted on ships and ocean buoys. NASA scientists analyze these measurements to account for uncertainties in the data and to maintain consistent methods for calculating global average surface temperature differences for every year.

These ground-based measurements of surface temperature are consistent with satellite data collected since 2002 by the Atmospheric Infrared Sounder (AIRS)[6] on NASA's Aqua satellite and with other estimates.

Many factors can affect the average temperature in any given year. For example, 2022 was one of the warmest on record despite a third consecutive year of La Niña conditions in the tropical Pacific Ocean. NASA scientists estimate that La Niña's cooling influence may have lowered global temperatures slightly [about 0.11 °F (0.06 °C)] from what the average would have been under more typical ocean conditions.

A separate, independent analysis by the National Oceanic and Atmospheric Administration (NOAA) concluded that the global surface temperature for 2022 was the sixth highest since 1880.[7] NOAA scientists use much of the same raw temperature data in their analysis and have a different baseline period (1901–2000) and methodology. Although rankings for specific years can differ slightly between the records, they are in broad agreement and both reflect ongoing long-term warming. NASA's full dataset of global surface temperatures through 2022, as well as full details with code of how NASA scientists conducted the analysis, are publicly available from GISS.[8] ■

[3] More information about NASA's EMIT mission can be found at ***earth.jpl.nasa.gov/emit*** or in "The Editor's Corner" of the July–August 2022 [**Volume 34, Issue 4, p. 1**—***eospso.nasa.gov/earthobserver/jul-aug-2022***] and September–October 2022 [**Volume 34, Issue 5, p. 3**—***eospso.nasa.gov/earthobserver/sep-oct-2022***] issues of *The Earth Observer*.

[4] See "Board 2090: Convenient Untruths—How We Underestimate Arctic Warming and How We Can Stop" at ***agu.confex.com/agu/fm22/meetingapp.cgi/Paper/1195179***.

[5] See "The Arctic has warmed nearly four times faster than the globe since 1979" at ***nature.com/articles/s43247-022-00498-3***.

[6] See "A Celebration of Twenty Years of AIRS History and Observations" in the September–October 2022 issue of *The Earth Observer* [**Volume 34, Issue 5, pp. 4–11**—***eospso.nasa.gov/earthobserver/sep-oct-2022***].

[7] See ***ncei.noaa.gov/news/global-climate-202212*** to learn more about NOAA's global surface temperature analysis for 2022.

[8] See ***data.giss.nasa.gov/gistemp*** to learn more about NASA's GISS Surface Temperature Analysis version 4 (GISTEMP v4) estimate of global surface temperature change.

NASA-ISRO Earth Science Instruments Get Send-Off Before Moving to India

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

It's nearly time for the scientific heart of the NASA–Indian Space Research Organisation (ISRO) Synthetic Aperture Radar [NISAR]—an Earth science satellite being jointly built by NASA and ISRO—to ship out to its last stop in southern India before launching into orbit.[1] Before its departure, members of the media got a chance to see NISAR's advanced radar instruments up close on February 3 in a clean room at NASA's Jet Propulsion Laboratory (JPL)—see **Photo 1**. Journalists spoke with **S. Somanath** [ISRO—*Chairman*], **Laurie Leshin** [NASA/JPL—*Director*], dignitaries from NASA headquarters and India, and members of the mission team.

"This marks an important milestone in our shared journey to better understand planet Earth and our changing climate," Leshin said. "NISAR will provide critical information on Earth's crust, ice sheets, and ecosystems. By delivering measurements at unprecedented precision, NISAR's promise is new understanding and positive impact in communities. Our collaboration with ISRO exemplifies what's possible when we tackle complex challenges together."

Somanath, **Sripriya Ranganathan** [*Indian Ambassador* and *Deputy Chief of Mission*], and NASA officials toured the High Bay 2 clean room, where they saw engineers and technicians putting the science instrument payload through final electrical testing.

Outside the facility, in front of a scale model of the NISAR satellite, **Phil Barela** [JPL—*NISAR Project Manager*] and **CV Shrikant** [ISRO—*NISAR Project Director*] ceremonially broke fresh coconuts. The tradition, common in India, often marks auspicious occasions and signifies hope for a smooth road ahead. Leshin also presented the ISRO delegation with a jar of JPL lucky peanuts.

Also present were **Bhavya Lal** [NASA Headquarters—*Associate Administrator for Technology, Policy, and Strategy*], **Karen St. Germain** [NASA HQ—*Director of the Earth Science Division*], and **Gerald Bawden** [NASA HQ—*NISAR Program Scientist*], among others.

[1] NISAR is a joint Earth-observing mission between NASA and ISRO. JPL leads the U.S. component of the project and is providing the mission's L-band SAR. NASA is also providing the radar reflector antenna, the deployable boom, a high-rate communication subsystem for science data, GPS receivers, a solid-state recorder, and payload data subsystem. ISRO is providing the spacecraft bus, the S-band SAR, the launch vehicle, and associated launch services and satellite mission operations. To learn more about NISAR, visit ***nisar.jpl.nasa.gov***.

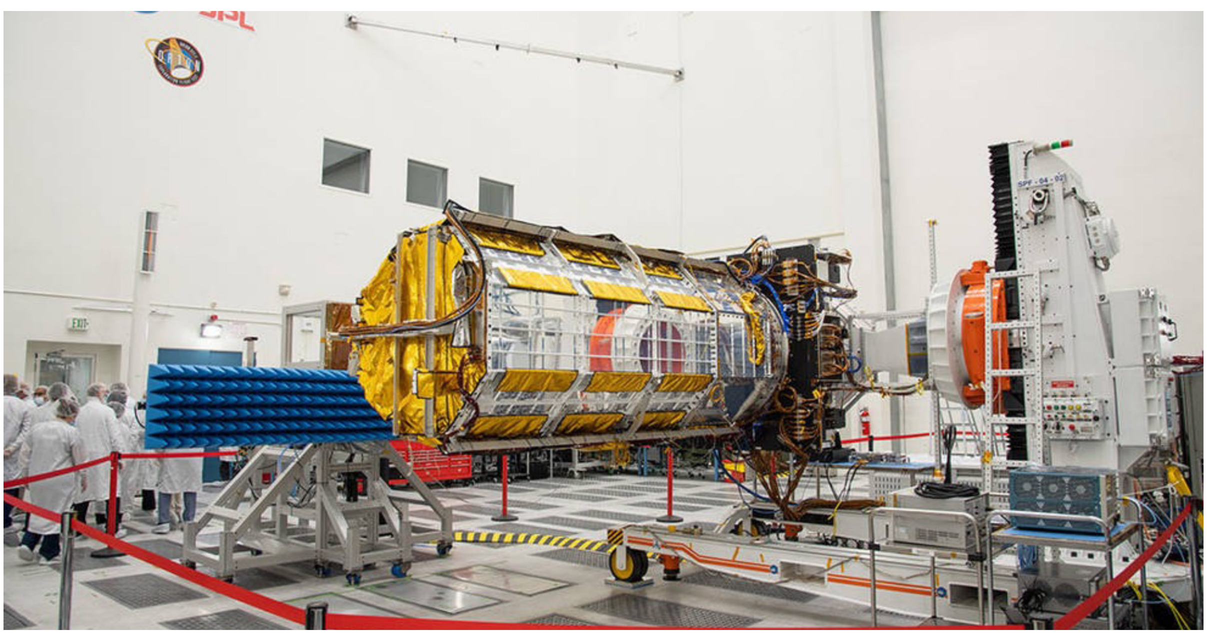

Photo 1. Officials from NASA, ISRO, and the Indian Embassy visit a NASA/JPL clean room to view the scientific instrument payload for the NASA–ISRO Synthetic Aperture Radar [NISAR] mission. **Photo credit:** NASA/JPL-Caltech

"Today we come one step closer to fulfilling the immense scientific potential NASA and ISRO envisioned for NISAR when we joined forces more than eight years ago," Somanath said. "This mission will be a powerful demonstration of the capability of radar as a science tool and help us study Earth's dynamic land and ice surfaces in greater detail than ever before."

Members of the media also visited the clean room, speaking with key figures on the NASA mission team, including **Wendy Edelstein** [JPL—*Deputy Project Manager*] and **Susan Owen** [JPL—*Deputy Project Scientist*].

NISAR will gather radar data with a drum-shaped reflector antenna almost 40 ft (12 m) in diameter. It will use a signal-processing technique called interferometric synthetic aperture radar (InSAR) to observe changes in Earth's land and ice surfaces down to fractions of an inch.

Since early 2021, engineers and technicians at JPL have been integrating and testing NISAR's two radar systems—the L-band SAR provided by JPL and the S-band SAR built by ISRO—see **Photo 2**. Later this month (February 2023), they will move the SUV-size payload into a special cargo container for a 9000-mile (14,000 km) flight to India's U R Rao Satellite Centre in the city of Bengaluru. There it will be merged with the spacecraft bus in preparation for a 2024 launch from Satish Dhawan Space Centre in Andhra Pradesh state.

The observations NISAR makes will help researchers measure the ways in which Earth is constantly changing by detecting both subtle and dramatic movements. Slow-moving variations of a land surface can precede earthquakes, landslides, and volcanic eruptions, and data about such movement could help communities prepare for natural hazards.[2] Measurements of melting sea ice and ice sheets will improve understanding of the pace and impacts of climate change, including sea level rise. And observations of the planet's forest and agricultural regions will improve our knowledge of carbon exchange between the atmosphere and plant communities, reducing uncertainties in models used to project future climate.

Over the course of its three-year prime mission, the satellite will observe nearly the entire planet every 12 days, making observations day and night, in all weather conditions.

"We have only just begun to envision the new knowledge and tangible benefits NISAR observations will have for communities around the world," St. Germain said. "This moment is the culmination of years of cooperation between NASA and ISRO and shows our shared commitment to advancing science and benefitting humanity." ■

[2] For more information about detecting earthquake precursor signals, please see the *Solid Earth Sciences* section of the "Summary of the GRACE Follow-On Science Team Meeting" on page 28 of this issue.

Photo 2. Engineers and technicians work on the science instrument payload for the NISAR mission in a JPL clean room. **Photo credit:** NASA/JPL-Caltech

NASA Earth Science in the News

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

An Inside Look at How NASA Uses Advanced Radar Technology to Better Understand Climate Change, February 20, 2023, ***cbsnews.com***

NASA is using its advanced technology to head for space—so it can monitor our home planet. In its latest climate report, the agency says 2022 was Earth's fifth-hottest year on record, part of a long-term warming trend attributed to climate change caused by humans. Some of its newest high-tech efforts will help gather more data on how our planet is changing.

In that vein, NASA is implementing a new Earth System Observatory,[1] featuring a series of five advanced satellite missions that will monitor nearly every aspect of Earth. It will give NASA a 3D view of how Earth's systems are operating and are impacted by climate change.

In December, NASA launched a rocket from Vandenberg Space Force Base in California carrying the Surface Water and Ocean Topography (SWOT) satellite. This $1.2 billion mission is the first radar to survey almost all of the world's surface water including nearly every ocean, river, lake, and stream on the planet. The satellite can survey six million bodies of water every three weeks.

In yet another foray into radar utility, NASA's upcoming joint satellite mission, the NASA–Indian Space Research Organisation (ISRO) Synthetic Aperture Radar [NISAR]—scheduled to launch next year—will use two different radar systems to track subtle changes in the Earth's surface to spatial resolution of less than a half-inch. This will allow better detection of ice sheet collapse and melting glaciers. The mission will also track deforestation, which contributes to global warming, as well as monitor groundwater supplies and even soil moisture, which can help predict the risk of wildfires.

NASA plans to share the data from all these missions with scientists and governments to help society better understand and adapt to climate change. ■

[1] More information about NASA's Earth System Observatory can be found at ***go.nasa.gov/3wmt4pm***.

NASA Space Missions Pinpoint Sources of Carbon Dioxide Emissions on Earth, January 9, 2023, ***phys.org***

A duo of Earth-observing missions has enabled researchers to detect and track carbon dioxide (CO_2) emission changes from a single facility, using the world's fifth-largest coal-fired power plant as a test case.

Researchers used space-based measurements from NASA's Orbiting Carbon Observatory–2 (OCO-2) and OCO-3 missions to quantify the CO_2 discharged hundreds of miles below at Bełchatów Power Station in Poland—the largest single emitter in Europe. Analyzing the plant's emission plumes from several satellite overpasses between 2017 and 2022, they detected changes in CO_2 levels that were consistent with hourly fluctuations in electricity generation. Temporary and permanent unit shutdowns (for maintenance or decommissioning) reduced the plant's overall emissions, which the team was able to detect as well.

Launched in 2014, NASA's OCO-2 satellite maps natural and human-made (anthropogenic) CO_2 emissions on scales ranging from regions to continents. The instrument samples the gas indirectly by measuring the intensity of sunlight reflected off Earth's surface and absorbed by CO_2 in the column of air from the ground to the satellite. The OCO-2 spectrometers are tuned to detect the specific signature of CO_2 gas.

Spare components from that mission were used to create OCO-3, an instrument that has flown on the International Space Station (ISS) since 2019. OCO-3 was designed with a mapping mode that can make multiple sweeping observations as the space station passes over an area, allowing researchers to create detailed mini-maps from a city-scale area of interest.

Neither OCO instrument was originally designed specifically to detect emissions from individual facilities such as Bełchatów. Most CO_2 emissions reports are created from estimates or data collected at the land surface. Researchers account for the mass of fossil fuels purchased and used, then calculate the expected emissions; they generally do not make actual atmospheric CO_2 measurements.

Because of the mapping mode observations of OCO-3, NASA data could be used more extensively in quantifying CO_2 point-source emissions in the future. NASA recently announced that mission operations will be extended for several more years aboard the space station, and the instrument will operate alongside another greenhouse gas observer aboard the space station, the Earth Surface Mineral Dust Source Investigation (EMIT).

California's Sierra Nevada Gives the Central Valley More Water than We Thought, January 31, 2023, ***kvpr.org***

While it's no secret that much of the California Central Valley's water supply comes from Sierra Nevada snowmelt, new research offers the first detailed accounting of the water that flows under the iconic mountain range.

"We're measuring how much water is gained and lost in California," says **Donald Argus** [NASA/Jet Propulsion Laboratory (JPL)], the lead author on a new study that shows more groundwater from below the Sierra is funneling into the Central Valley's aquifers than previously thought.[2] The data has potentially big implications for water managers.

NASA's research shows the Sierra's mere presence is slowly helping recharge overtapped aquifers in the face of drought. "It looks like there's more recharge, and more emptying of water for irrigation than we had previously thought. It's a wash," Argus says.

This means if water managers are able to conserve more groundwater, those supplies should recharge more quickly than anticipated thanks to help from the previously unstudied amounts of water coming from the Sierra.

To get the total, Argus's team used data from NASA's Gravity Recovery and Climate Experiment (GRACE) mission—a pair of satellites that measured minute variations in Earth's gravitational field from 2002–2017.[3] This allows scientists using complex mathematics to infer changes in runoff and groundwater over large land masses, such as the Sierra.

Approximately 13.2 trillion gallons of water—about 20 million full Olympic-sized swimming pools—enter the Central Valley each year between Sierra snowmelt, rainfall, and other sources. Of that total, about 10% flows underground into aquifers that provide groundwater to the San Joaquin Valley. That water has helped the region become the nation's fruit basket despite a naturally arid climate.

But there's a catch. The amounts of water that NASA researchers recently studied can take decades to flow from mountain peaks to underground aquifers deep below the Valley. In the meantime, certain regions of Central California are losing groundwater more quickly than others. More than two-thirds of depleted groundwater is concentrated in the southern San Joaquin Valley, Argus says. The data exploring water from below the Sierra is important. While the Central Valley contains only 1% of the nation's farmland, the region produces 40% of its fresh fruits and vegetables.

Cyclones in the Arctic Are Becoming More Intense and Frequent, January 17, 2023, ***sciencenews.org***

In January 2022, a cyclone blitzed a large expanse of ice-covered ocean between Greenland and Russia. Frenzied gusts galvanized 8 m (26 ft) waves that pounded the region's hapless flotillas of sea ice, while a bombardment of warm rain and air from the south laid siege from the air. Six days after the assault began, about a quarter of the vast area's sea ice had disappeared, leading to a record weekly loss for the region. The storm is the strongest Arctic cyclone ever documented—but it may not hold that title for long.

Cyclones in the Arctic have become more frequent and intense in recent decades, posing risks to both sea ice and people, researchers reported at the 2022 American Geophysical Union (AGU) fall meeting. The Arctic Circle is warming about four times as fast as the rest of Earth. A major driver is the loss of sea ice due to human-caused climate change. The floating ice reflects far more solar radiation back into space than naked seas do, influencing the global climate.

During August, the heart of the sea ice melting season, cyclones have been observed to amplify sea ice losses on average, exacerbating warming. Like hurricanes can ravage regions farther south, boreal vortices can threaten people living and traveling in the Arctic, forcing some communities to relocate inland.

Climate change is intensifying storms farther south. However, it's unclear how Arctic cyclones might be changing as the world warms. Some previous research suggested that pressures, on average, in Arctic cyclones' cores have dropped in recent decades. That would be problematic, as lower pressures generally mean more intense storms.

But inconsistencies between analyses had prevented a clear trend from emerging, so the research team aggregated a comprehensive record—see **Figure** on page 44—spanning 1950–2021, of Arctic cyclone

[2] The study can be found at ***agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL099583***.
[3] More information about NASA's GRACE mission can be found at ***nasa.gov/mission_pages/Grace/index.html***.

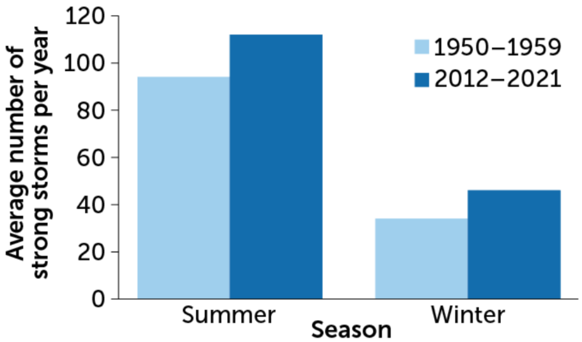

Figure. The seasonal frequency of strong Arctic cyclones in the 1950s and 2010s. **Figure credit.** Erin Orwell/Science News, based on info provided by Xiangdong Zhang/University of Alaska Fairbanks.

timing, intensity, and duration. Arctic cyclone activity has intensified in strength and frequency over recent decades, and pressures in the hearts of today's boreal vortices are on average about 9 mb lower than in the 1950s. For context, such a pressure shift would be roughly equivalent to bumping a strong Category 1 hurricane well into Category 2 territory.

Further, vortices became more frequent during winters in the North Atlantic Arctic and during summers in the Arctic north of Eurasia. In the last decade, strong vortices—with central pressures lower than 990 mb—appeared in the Arctic more often each year, on average, than in the 1950s, up about 20% in the summer and 35% in the winter.

What's more, August cyclones appear to be damaging sea ice more than in the past, according to the U.S. Naval Research Laboratory, where a team compared the response of northern sea ice to summer cyclones during the 1990s and the 2010s. August vortices in the latter decade were followed by a 10% loss of sea ice area on average—up from the earlier decade's 3% loss on average. This may be due, in part, to warmer water upwelling from below, which can melt the ice pack's underbelly, and from winds pushing the thinner, easier-to-move ice around.

Such phenomena may have intensification effects in spring, too. That's a problem because spring vortices can prime sea ice for later summer melting.

By the end of the century, the maximum near-surface wind speeds of spring cyclones—around 7 mph (11 kph) today—could reach 37 mph (60 kph), the researchers found. And future spring cyclones may keep swirling at peak intensity for up to a quarter of their life spans, up from around 1% today. The storms will probably travel farther too, the team says.

The team plans to investigate the future evolution of Arctic cyclones in other seasons, to capture a broader picture of how climate change is affecting the storms. For now, it seems certain that Arctic cyclones aren't going anywhere. What's less clear is how humankind will contend with the storms' growing fury. ■

Earth Science Meeting and Workshop Calendar

NASA Community

May 1–5, 2023
MODIS–VIIRS Calibration Workshop and Science Team Meeting
College Park, MD
modis.gsfc.nasa.gov/sci_team/meetings/202305

May 1–5, 2023
Joint Science Meeting for TEMPO, GeoXO ACX, and TOLNet
Huntsville, AL
weather.ndc.nasa.gov/tempo/events/2023-joint-science-meeting

May 9–11, 2023
CERES Science Team Meeting
Hampton, VA and online
ceres.larc.nasa.gov/ceres-science-team-meetings

May 23–25, 2023
Terra, Aqua, and Aura Data Continuity Workshop, *virtual*

October 16–20, 2023
2023 Sun-Climate Symposium
Flagstaff, Arizona
lasp.colorado.edu/home/meetings/2023-sun-climate-symposium

Global Science Community

April 23–28, 2023
European Geosciences Union (EGU) 2023 General Assembly
Vienna, Austria, and *online*
egu23.eu

July 16–21, 2023
International Geoscience and Remote Sensing Symposium
Pasadena, CA
2023.ieeeigarss.org

July 30–August 4, 2023
Asia Oceania Geosciences Society
Singapore
asiaoceania.org/aogs2023/public.asp?page=home.asp

Code 610
National Aeronautics and Space Administration

Goddard Space Flight Center
Greenbelt, MD 20771

eospso.nasa.gov

The Earth Observer

The Earth Observer is published by the Science Support Office, Code 610, NASA's Goddard Space Flight Center (GSFC), Greenbelt, MD 20771. PDFs of previous issues (from March–April 1999 to the present) are available at *eospso.nasa.gov/earth-observer-archive*.

Article submissions, contributions to the meeting calendar, and other suggestions for content are welcomed. Contributions to the calendars should contain date, location (if meeting in person), URL. Also indicate if the meeting is *hybrid* (combining online and in person participation) or *virtual* (online only). Newsletter content is due on the weekday closest to the fifteenth of the month preceding the publication—e.g., December 15 for the January–February issue; February 15 for March–April, and so on.

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