Over Thirty Years Reporting on NASA's Earth Science Program

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Editor's Corner

Steve Platnick

EOS Senior Project Scientist

As of this writing, the world is in the midst of a pandemic caused by the current novel coronavirus disease (COVID-19). Society is engaging in an unprecedented experiment in extreme social and physical distancing in an attempt to contain the spread of the virus. With health and safety of paramount concern, all NASA facilities are currently at *Stage 3* or *Stage 4* of a four-stage Response Framework.[1] Stage 4 is the maximum level of response with mandatory telework for the vast majority of personnel as facilities are closed to all but essential activities necessary to protect life and critical infrastructure. Note that Earth science mission operations are considered essential.

Fortunately, most NASA personnel are able to continue to do their jobs remotely, including the staff of *The Earth Observer* newsletter who are doing their best to stay on schedule with production of this and future issues despite the exceptional circumstances. While many face-to-face meetings are cancelled or postponed, online conferencing is proliferating. So, as it has done for more than 30 years, this newsletter will endeavor to continue reporting on NASA Earth science meetings and other activities.

Despite world-wide social distancing, NASA (and international partner) satellites continue to acquire data, some of which can detect COVID-19 impacts. The pair of images [*below*] show a recent example from the Ozone Monitoring Instrument (OMI) on NASA's Aura satellite. They show the dramatic change in average nitrogen dioxide (NO_2) concentrations over the Northeast U.S. in March 2020, as compared to the average monthly NO_2 concentrations during March from 2015 through 2019—see **Figure**.

On the subject of observing pollution from space, NASA, South Korea, and the European Space Agency (ESA) are working together on a constellation of geosynchronous platforms to document trace gases and air quality in unprecedented detail.[2] The first instrument in this constellation to launch was the Korea Aerospace Research Institute's (KARI) Geostationary Environment Monitoring Spectrometer (GEMS). This UV-Visible spectrometer launched on February 18, 2020 on South Korea's GEO-KOMPSAT-2B satellite.[3] Meanwhile, in a briefing on

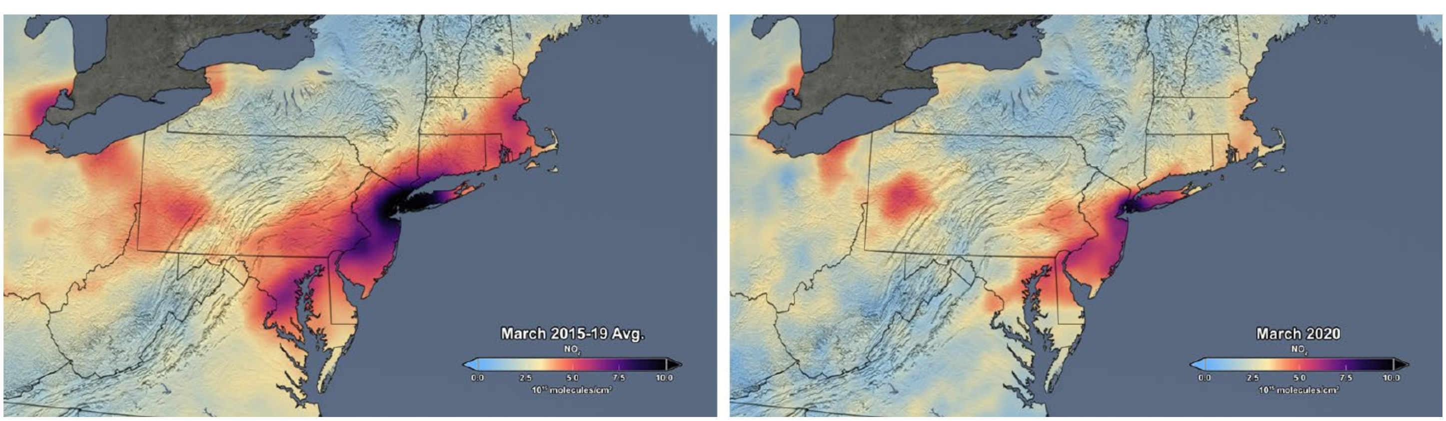
[1] This framework is explained at *https://go.nasa.gov/2VDcuk4*; the status of each center and other information about NASA's coronavirus response can be found at *https://nasapeople.nasa.gov/coronavirus/coronavirus.htm*.

[2] To learn more about plans for this constellation, read "NASA Ups the TEMPO on Monitoring Air Pollution" in the March–April 2013 issue of *The Earth Observer* [**Volume 25, Issue 2**, pp.10–15—*https://go.nasa.gov/2WGStuX*].

[3] GEO-KOMPSAT-2B has three other instruments onboard, and is also focused on ocean-surface monitoring.

continued on page 2

Figure. These images show a reduction in nitrogen dioxide (NO_2) levels as measured by the Ozone Monitoring Instrument (OMI) on Aura over the Northeast U.S. in March 2020. The image on the left shows average monthly NO_2 concentrations during March from 2015 through 2019, while the image on the right shows average monthly concentrations in March 2020. Though variations in weather from year to year cause variations in the monthly means for individual years, March 2020 shows the lowest values as compared to any of the monthly values for March during the OMI data record, which spans 2005 to present. These recent improvements in air quality have come at a high cost, as communities grapple with widespread lockdowns and shelter-in-place orders as a result of the spread of COVID-19. The data indicate that the NO_2 levels in March 2020 are about 30% lower on average across the region of the I-95 corridor from Washington, DC to Boston, MA than when compared to the mean of 2015 to 2019. For more information, visit *https://airquality.gsfc.nasa.gov*. **Credit**: GSFC



In This Issue

Reminder: To view newsletter images in color, visit *eospso.nasa.gov/earth-observer-archive.*

March 9, NASA announced plans to send the nearly identical Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument into space aboard a commercial communications satellite in 2022. GEMS and TEMPO will be followed by ESA's Copernicus Sentinel-4A and -4B missions carrying identical spectrometers launching several years apart; Sentinel-4A is scheduled for launch in 2023.[4] The measurements from these geosynchronous instruments complement other existing trace gas and aerosol observations from satellites in low Earth orbit and ground networks. In particular, data from geosynchronous orbits will better capture diurnal variability (e.g., transportation sector) and episodic events.

On a related retrospective note about UV measurements, April 8, 2020, marked the fiftieth anniversary of the launch of Nimbus-4, which flew the Backscatter UV (BUV) instrument. BUV's successful demonstration of column ozone retrievals laid the foundation for future UV-based ozone observations, from NASA's Total Ozone Mapping Spectrometer (TOMS) instruments to the OMI on Aura and the Tropospheric Monitoring Instrument (TROPOMI) on Sentinel-5P, to the operational Ozone Mapping Profiler Suite (OMPS) instruments. More information about the historic BUV on Nimubs-4 can be found in a NASA Earth Observatory's *Earth Matters* blog to coincide with the launch anniversary.[5]

In a *Twitter* post on December 28, 2019, **NASA Administrator Jim Bridenstine** announced that NASA's Geostationary Carbon Cycle Observatory (GeoCarb) was confirmed to continue to Phase C of its mission development. GeoCarb builds on the success of NASA's successful OCO-2 mission by placing a similar instrument in geostationary orbit as a hosted payload. The geostationary vantage point (34,500 km altitude) will allow GeoCarb to scan the entire continental U.S. in about 2 hours and 15 minutes, and from Brazil to South America's West Coast in about 2 hours and 45 minutes. It is not designed to observe the ocean, as reflectivity over the ocean is too low to provide useful data. Measurements from GeoCarb will complement those from OCO-2 which is in a Sun-synchronous polar orbit (1:30 PM local time, 705 km altitude). While the OCO-2 polar orbit provides high latitude coverage, the revisit time to any particular orbit track location is every 16 days, as is the case for other Afternoon constellation, or "A-Train," satellites. By comparison, GeoCarb will scan the Western Hemisphere at least once per day and capture changes to the carbon cycle on weather time scales.

Chosen as the winning Earth Venture Mission–2 (EVM-2) proposal in 2016, the primary goals of GeoCarb are to monitor plant health and vegetation stress throughout the Americas, and to probe, in unprecedented detail, the natural sources, sinks, and exchange processes that control carbon dioxide, carbon monoxide, and methane in the atmosphere. The Principal Investigator for the mission is **Berrien Moore** [University of Oklahoma] with GSFC providing project management. More details about GeoCarb can be found at *http://www.ou.edu/geocarb*.

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[4] This date is reported in a press release at *https://go.nasa.gov/2V5j5EJ*.

[5] To read the blog entry, see *https://go.nasa.gov/3bezDQw*. To learn more about the history and accomplishments of NASA's Nimbus Program, see "Nimbus Celebrates Fifty Years" in the March–April 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 2**, pp. 18–30—*https://go.nasa.gov/3a9YUd7*].

On February 26, 2020, NASA HQ announced the first Earth Venture Continuity (EVC-1)[6] mission selected in response to recommendations made by the 2017 National Academies' Earth Science Decadal Survey.[7] The new instrument will be called Libera; the name pays homage to the instrument's heritage. In Roman mythology, Libera was the daughter of Ceres, the goddess of agriculture. For NASA, Libera will be the "the heir," or follow-on, to the highly successful series of Clouds and the Earth's Radiant Energy System (CERES) instruments. Libera will measure top of the atmosphere reflected solar radiation with wavelengths between 0.3 and 5 μm and emitted infrared radiation between 5 and 50 μm, along with a combined reflected plus emitted radiation channel from 0.3 to 100 μm. An additional 0.7 to 5 μm channel is included to enable new Earth radiation budget science.

Libera will fly on NOAA's operational Joint Polar Satellite System-3 (JPSS-3) satellite, which is scheduled to launch by December 2027. The project's Principal Investigator is **Peter Pilewskie** [University of Colorado (CU) Laboratory for Atmospheric and Space Physics (LASP)]. Libera was selected competitively from the EVC-1 Announcement of Opportunity. EVC missions are intended to focus on demonstrating innovative, low-cost approaches to maintaining targeted, unbroken, and consistent time series of measurements of key environmental parameters (e.g., radiation balance) that are important for climate change studies.

In news related to satellite missions already in orbit, NASA's Solar Radiation and Climate Experiment (SORCE) science mission ended on February 25, 2020 after completing more than 17 years of exceptional observations of the total solar irradiance (TSI) and spectral solar irradiance (SSI) between 1–2400 nm. This was a planned passivation event now that NASA's newer Total and Spectral Solar Irradiance Sensor (TSIS-1) mission has obtained its required overlap with SORCE. TSIS-1, aboard the International Space Station (ISS), will be continuing the four-decade-long TSI climate data record, as well as continuing the SSI 200–2400 nm climate data record that SORCE initiated for the 400–2400 nm range. These TSI and SSI measurements are key inputs for atmosphere and climate modeling, energy balance modeling, and remote sensing. The length of the SORCE mission's longevity enabled measurements in two of the Sun's 11-year solar cycles, and SORCE observed solar cycle minimum conditions in both 2008 and 2019 that are particularly useful for secular trending of the solar irradiance.

[6] See EVC-1 press release on page 36 of this issue.

[7] The 2017 Earth Science Decadal Survey is available at *https://essp.nasa.gov/essp/files/2018/02/2017-Earth-Science-Decadal-Survey.pdf*; a PDF can be downloaded from *http://nap.edu/24938*.

SORCE does not have any onboard propulsion (i.e., fuel), therefore, it was not possible to perform a controlled re-entry as part of the decommissioning activities. The passivation involved powering off instruments and most spacecraft systems and disabling the spacecraft reaction wheels and radio communication systems. SORCE's orbit will slowly decay due to atmospheric drag; it is expected to re-enter and burn up in the atmosphere in 2032.

Congratulations to the CU LASP engineers and scientists for leading, implementing, and operating the remarkable SORCE mission[8] along with long-standing support from NASA HQ and GSFC. A special kudos to the operations team at CU LASP and Northrop Grumman (formerly Orbital Sciences Corporation when the SORCE spacecraft bus was built) for their dedication and resourcefulness in continuing the SORCE mission well past its expected five-year lifetime, especially after battery capacity issues and an anomaly with one of the reaction wheels threatened to end the mission before TSIS was launched.

Finally, in our last issue we reported on a *Symposium on Earth Science and Applications from Space with Special Guest Michael Freilich* that took place January 21, 2020, at the National Academy of Sciences in Washington, DC. The event was organized to pay tribute to the career of **Michael Freilich** who was director of the Earth Science Division at NASA HQ from 2006–2019, capping off a long and distinguished career in ocean research that spanned nearly 40 years. During his career, Freilich was also a mentor for many other scientists and scientific leaders, many of whom attended the Symposium. Freilich, his wife, and other family members were in attendance. We are delighted to refer you to the lead article in this issue that provides a detailed summary of the symposium (please see page 4). ■

[8] To learn more about the remarkable achievements (from the first ten years) of SORCE, see "The SORCE Mission Celebrates Ten Years," in the January–February 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 1**, pp. 3-13—*https://go.nasa.gov/3bbPZck*].

See page 43 for a list of undefined acronyms used in the Editorial and/or Table of Contents.

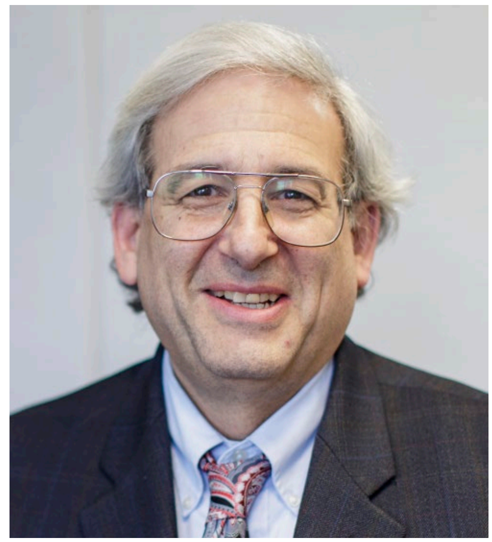
Symposium on Earth Science and Applications from Space with Special Guest Michael Freilich

Alan B. Ward, NASA's Goddard Space Flight Center/Global Science & Technology Inc., alan.b.ward@nasa.gov

*As director of the Earth Science Division at NASA Headquarters from 2006–2019, and throughout nearly 40 years of ocean research, **Michael "Mike" Freilich** helped train and inspire the next generation of scientists and scientific leaders.*

Introduction

On January 21, 2020, a *Symposium on Earth Science and Applications from Space* took place in the Kavli Auditorium at the National Academy of Sciences Building in Washington, DC, to pay tribute to **Michael Freilich** [NASA Headquarters (HQ), Retired—*Former Director of NASA's Earth Science Division* from 2006 to 2019]. As director of the Earth Science Division and throughout nearly 40 years of ocean research, Freilich helped train and inspire the next generation of scientists and scientific leaders. Freilich, his wife Shoshannah, and other family members attended.



After several opening presentations, a significant portion of the day was given over to a series of eight focus-area presentations that concentrated on research in which Freilich was actively involved and/or played an important support role. In addition, three afternoon panel discussions emphasized lessons learned from panelists' interactions with Freilich, international collaboration, as well as new directions and innovations for future Earth science research and data applications. The meeting ended with a summary of the day's events and remarks from the guest of honor.

This report summarizes the highlights from this all-day symposium. A video of the livestream is available at *https://go.nasa.gov/395OieG*.

Opening Presentations

Colleen Hartman [National Academy of Sciences, Engineering, and Medicine (NASEM)—*Director of the Space Studies Board and the Aeronautics and Space Engineering Board*] moderated the symposium. She opened the meeting, welcoming the participants and the guest of honor, **Michael Freilich,** whom many knew as "Mike," and to which he will be referred henceforth in this report. Hartman also welcomed Mike's family and encouraged energetic interaction during the breaks.

Marcia McNutt [National Academy of Sciences (NAS)—*President*] described her working relationship with Mike when she was head of the U.S. Geological Survey (USGS). They first met after the massive Deepwater Horizon oil release in 2010, when NASA satellites provided aircraft and satellite observations that were key to understanding the full impact of the disaster. McNutt said that her most meaningful interaction with Mike was during the development of the joint USGS–NASA Landsat Data Continuity Mission, later renamed Landsat 8. As a fitting finale, her last official act as USGS director was to oversee the Landsat 8 launch. A clear message she wanted to deliver was that Mike oversaw an organization filled with high-quality people and producing high-quality data.

Thomas Zurbuchen [NASA HQ—*Associate Administrator of the Science Mission Directorate (SMD)*] noted that the study of our home planet has been part of NASA's mandate from its inception, and that those few who get to visit space get a unique perspective as they view the planet we call home from above. Zurbuchen said he was excited to celebrate Earth science today—and in particular the role Mike has played. His remarks emphasized three qualities that characterized Mike's tenure—leadership, partnership, and mentorship—and gave examples of each:

- *Leadership*. Mike led a cultural transformation of NASA Earth Science, with the development of the Earth Venture program[1] as an example. Mike's leadership extended beyond the Earth Science Division: he provided leadership across the entire SMD. Zurbuchen said that he is better at his job—and more thoughtful about Earth science and science in general—because of Mike. He noted that while Mike's daily presence at NASA HQ is missed, his legacy continues.

- *Partnership*. Mike both strengthened existing domestic and international partnerships and established new ones. Zurbuchen cited the development of the SWOT and NISAR missions as specific examples.[2]

- *Mentorship*. Mike has a mentoring instinct, honed from years of experience as a teacher and academic leader prior to joining NASA. He was effective at gently instructing many with whom he came into contact—including Thomas himself!

Zurbuchen then summarized his presentation and closed his remarks by saying that the full impact Mike has had on NASA Science is yet to come—i.e., it will be realized when future missions (e.g., SWOT, NISAR), in which he played a key planning role, finally launch.

***Thomas Zurbuchen** said he was excited to celebrate Earth science today—and in particular the role Mike has played. His remarks emphasized three qualities that characterized Mike's tenure—leadership, partnership, and mentorship.*

Dudley Chelton [Oregon State University] gave a lighthearted but thorough and moving keynote presentation called *From Cello to Nonlinear Shoaling Waves to Air-Sea Interaction and Beyond: A Synopsis of Mike Freilich's Global Vision and Impact on NASA Earth Science from Space*. (This presentation begins at 18:10 of the livestream.) Chelton described how he first met Mike in 1975, when they were in graduate school together. He showed photos including pictures of Mike in childhood, e.g., playing cello; shared memories and anecdotes from backpacking trips he and Mike took to the Sierras; and showed the cover of Mike's doctoral thesis and his first publication. **Figure 1** on page 6 shows a collage of different images shown during this presentation.

Chelton then went on to discuss Mike's early career at NASA/Jet Propulsion Laboratory (JPL), from 1982–1993, where he was project scientist for the NASA Scatterometer (NSCAT), and at Oregon State University, from 1992–2006, where he was principal investigator (PI) for NASA's SeaWinds instrument.[3] He then discussed Mike's tenure at NASA HQ from 2006–2019, noting that Mike was the longest-serving director of the Earth Science Division (which was previously known as Mission to Planet Earth, and later the Earth Science Enterprise). Chelton pointed out that Mike never sought credit for his accomplishments—preferring to give credit to others—but the results of his time at NASA speak for themselves. Mike inherited a program that had faced years of budget cuts, but he fostered and oversaw a nearly 50% increase in NASA Earth Science's budget during his 13 years of leadership.

Chelton then shifted his focus to Mike's contributions to the field of scatterometry. He mentioned the Quick Scatterometer (QuikSCAT) mission, so named because it was rapidly created after the unexpected failure of NSCAT [due to power failure of the Japanese Advanced Earth Observation Satellite (ADEOS) platform]. As Chelton

[1] Earth Venture missions are a class of science-driven, competitively selected, low-cost missions that were in the first (2007) Earth Science Decadal Survey.

[2] SWOT stands for Surface Water and Ocean Topography; the mission is being jointly developed by NASA and the French Centre National d'Études Spatiales (CNES), with contributions from the Canadian Space Agency (CSA) and the U.K. Space Agency; it is scheduled to launch in 2021. NISAR stands for NASA–Indian Space Research Organisation (ISRO) Synthetic Aperture Radar, which is scheduled for launch in 2022.

[3] SeaWinds flew on NASA's Quick Scatterometer (QuikSCAT) mission (1999–2009) and on the Japan Aerospace Exploration Agency's (JAXA) Advanced Earth Observation Satellite–II (ADEOS-II) mission (2002–2003), which lasted less than a year due to a spacecraft power failure.

Figure 1. *Photo collage of Michael "Mike" Freilich.* Dudley Chelton was a colleague and is a close friend of Mike. He gave a lighthearted but thorough and moving keynote presentation during the symposium in which he provided a synopsis of Mike's career and major research contributions, as well as giving participants a glimpse into Mike's life outside of work. The photos in this collage were all part of Chelton's presentation. Beginning in the upper left and moving clockwise, they include several scenes from Mike's childhood; several photos of Mike at play (taken by Chelton on back-packing expeditions they took together to the Sierras); two of Mike at work during his NASA tenure (one of him speaking in front of the NASA Hyperwall, and another of him speaking to the media in front of the White House); and two photos (one from the past and one from the present) of Mike and his beloved wife, Shoshannah. **Photo credit:** Dudley Chelton

put it, "QuikSCAT was a three-year mission—that lasted ten years!" He credited Mike with discovery of an air–sea interaction phenomenon that was made possible from analysis of QuikSCAT data, namely that the magnitudes of wind stress and sea surface temperature (SST) are positively correlated on oceanic mesoscales (~100–1000 km). This led to the finding that the ocean and atmosphere are a fully coupled, two-way system on these scales, which in turn led to the discovery that the wind field in marine atmospheric boundary layers is significantly impacted by SST, and that the feedback of these wind perturbations significantly affects ocean circulation. As an example, Chelton showed the influence of SST on winds over the California current, a topic that Chelton himself has been passionate about since writing his PhD thesis four decades ago.

Chelton thanked Shoshannah for her support of Mike over the years, who couldn't do all that he did for Earth Science if he had not had a supportive wife and family.

To close, Chelton, a self-confessed "email packrat," shared a correspondence Mike had sent him—from 1998!—in which Mike had said "A pessimist is an optimist in full possession of the facts."

A pessimist is an optimist in full possession of the facts.
—***Mike Freilich***
[in an email to Dudley Chelton from 1998]

William Gail [Global Weather Corporation—*Co-Chair of 2017 Earth Science Decadal Survey*] discussed the development of the Earth Science Decadal Survey (ESDS). NASEM considers Decadal Survey reports some of the most important documents the organization produces—see **Figure 2**. These Surveys had their origin with the Astronomy Decadal Surveys, which date back to 1964; other science disciplines followed. Earth Science is a relative latecomer to the process, producing its first ESDS in 2007 and its second in 2017.[4] Mike was involved in the production of both ESDS reports, but he was particularly influential in shaping the second one.

Figure 2. *Decadal Survey covers.* Shown here are the covers of several National Academy of Sciences, Engineering, and Medicine (NASEM) Decadal Survey reports; the 2017 Earth Science Decadal Survey (ESDS) is shown on the right. Mike Freilich had an important leadership role in the formation of the 2007 and the 2017 ESDS reports. **Image credit:** William Gail

Gail started with a reminder of the situation before the first ESDS. In the early 2000s the foundational—or *First Series* of—Earth Observing System (EOS) satellite missions[5] neared completion, and the next step was unclear.[6] There had been a 50% drop in NASA's Earth Science budget during the 1990s (as EOS was ramping up), necessitating significant changes to the EOS Program.[7]

[4] Both the first (2007), "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," and second (2017) Decadal Surveys, "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observations from Space," are available for download at *https://go.nasa.gov/2wXJn2n*.

[5] The original EOS concept envisioned a series of identical missions that would be repeated three times over 15 years. The "First Series" included AM-1 (now known as *Terra*), PM-1 (*Aqua*), and CHEM-1 (*Aura*), among others. In light of shrinking budgets in the 1990s, the series concept was abandoned. The desired continuity has been achieved by using new approaches (e.g., constellation flying) and by the remarkable durability of the "first series" satellites—which have all lasted over 15 years!

[6] The "Perspectives on EOS" series of articles, published in *The Earth Observer* from 2008–2011, documents the evolution of EOS from the viewpoints of key figures in the program as it was being developed and implemented. The articles can be downloaded from *https://eospso.nasa.gov/earthobserver/perspectives-eos*.

[7] See Mark Abbott's *Perspectives on EOS* article (beginning on page 41 at the link in footnote 6) for more details on the changing shape of EOS in the mid-1990s.

On the whole, Gail said, the Earth science community was skeptical about doing a Decadal Survey. Although they had been successful in other science disciplines, it was far from certain how well such a report would work to guide Earth Science. Gail explained how the outcome of a workshop held at Woods Hole Oceanographic Institution (WHOI) in August 2004 provided a framework for the first ESDS. Although progress was slow and there were real challenges that had to be overcome, from early on there was emphasis on understanding the Earth as a system, and agreement that societal benefits would be a crucial theme. An interim report on progress on the first ESDS issued in 2005 used dire language to describe the danger of not acting decisively—and soon—stating that "Today [2005] the current system of [U.S. civilian Earth observing] satellites is at risk of collapse."[8]

"Understanding the complex, changing planet on which we live, how it supports life, and how human activities affect its ability to do so in the future is one of the greatest intellectual challenges facing society."
—2007 Earth Science Decadal Survey

The first ESDS opened with the compelling statement found in the margin [*left*]. The structure was organized around this vision. It identified 17 missions, distributed into three tiers (corresponding to priority levels), and mapped into nine societal challenges.

Gail reported that, "NASA responded favorably and aggressively to the first ESDS," adding that, "We [the organizers of the first ESDS] were pleasantly surprised that it didn't tear the community apart—but neither did it bring them together. That job fell on Mike's shoulders." Despite challenges, 2007–2016 (which overlaps with the majority of Mike's time at NASA) was a period of progress for NASA Earth Science and set the stage for the second ESDS, which Gail described as "…easier in some ways and harder in others." On the one hand, there was now a healthy Earth observation system in place, a template to follow (after the first ESDS), and more community support than before. However, because the first ESDS succeeded in prioritizing the activities of the Earth Science community, the bar for success was set higher for the second in that the community expected more from the new survey. Also, the budgets were much more constrained.

Gail discussed development of the second ESDS, noting that authors made a decision to focus less on specific missions and more on *targeted observables*—with five prioritized as *Designated Observables*, and seven others called *explorers*. He then gave an overview of the various parts of the second ESDS. Gail said Mike's fingerprints are everywhere in the structure of the second ESDS. For example he played a key role in overseeing development of The Science and Applications Traceability Matrices (SATM)—see *Appendix B* of the second ESDS—that provided the basis for much of the Steering Committee's deliberations and formed the foundation of their recommendations.

I have much to say about the [Decadal Surveys], ranging from fantastic to monumental in terms of their guidance and especially their domestic impact.
—***Mike Freilich*** [in an email to Bill Gail, January 4, 2020]

In summary, Gail said that the two ESDS reports have advanced Earth-system-related disciplinary science and contributed to the longstanding EOS goal of understanding Earth as a system. His overall assessment pretty much says it all: "We've come far, we've learned much—and Mike Freilich's role has been enormous."

Science Focus Area Presentations

Colleen Hartman introduced this session, which consisted of eight presentations, each focusing on a particular NASA Science research focus area. Along the way, the speakers described the important role that Mike played in achieving the outstanding success in these areas. The speakers all acknowledged Mike's interactions with them personally and/or his support of particular missions. As an example, in her remarks, **Paula Bontempi** [NASA HQ—*Acting Deputy Director of the Earth Science Division*] echoed the remarks of two chief scientists who independently said, "When Mike is in

[8] This report, "Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation" can be downloaded from *https://go.nasa.gov/3a478Eu*.

the room, he raises the game of everyone in the room." Likewise, **Graeme Stephens** [JPL—*CloudSat PI*] thanked Mike for "having Earth science's back" for all these years. The **Table** below summarizes the presentations given during this session.

Table. Science focus-area presentation topics, speakers, and summaries. The Table continues on page 10. Footnotes and a list of undefined acronyms are on page 11.

Topic	Speaker [Affiliation]	Presentation Summary
GRACE Observations of Earth System Mass Change	**Byron Tapley** [University of Texas, Retired—*GRACE PI*]	Discussed the GRACE mission (2002–2017) with emphasis on Mike's role in its development. GRACE operated for 15 years—long beyond the planned end of its 5-year mission—and generated 163 monthly solutions, which established measurements of Earth system mass change as an essential climate change measurement. Showed how the fine-scale detail of the mean gravity field has improved significantly since launch—and even more when combined with European GOCE mission. Summarized the many applications where GRACE data have been used, and showed a number of specific examples—e.g., ice loss, ocean mass change, land surface water storage, major earthquakes, and hydrological applications. Discussed GRACE–Follow On (launched in 2018), which has now produced 16 gravity solutions. Looking to the future, Mass Change is one of the Designated Observables identified for continuity by the 2017 ESDS.
Watching the Ocean Breathe: The Genesis of PACE	**Paula Bontempi** [NASA HQ—*PACE Program Scientist* and *Acting Deputy Director of the Earth Science Division*]	Discussed the legacy of the PACE mission, which is now in Phase C of development, including the heritage missions and instruments (e.g., CZCS, SeaWiFS, MODIS, VIIRS) and the history of its development, in which Mike played a key role. Explained how this ocean-color time series has helped to establish a strong link between ocean climate and primary production. Showed a data visualization that depicts the Earth "breathing" (*https://svs.gsfc.nasa.gov/703*), and noted that continued PACE activities should take observations to the next level, e.g., allowing us to distinguish different types of phytoplankton.
Planet Ocean: Taking the Pulse of Our World	**R. Steven Nerem** [University of Colorado]	Discussed the satellite altimetry climate data record, beginning in 1993 with TOPEX/Poseidon, continuing with Jason-1, -2, and -3, and further continuing with Sentinel-6/Jason-Continuity of Service (CS).‡ Explained that altimetry data are what helps scientists determine the magnitude and causes of sea-level change. Over the last three decades more than 1000, ten-day, mean-sea-level maps have been produced, which have been combined to produce a global mean-sea-level-variation plot that includes data from all the missions—see **Figure 3** below. Showed a breakdown of the components of the sea-level budget that clearly shows that ice losses in Greenland and Antarctica are the primary drivers of accelerating sea-level rise.

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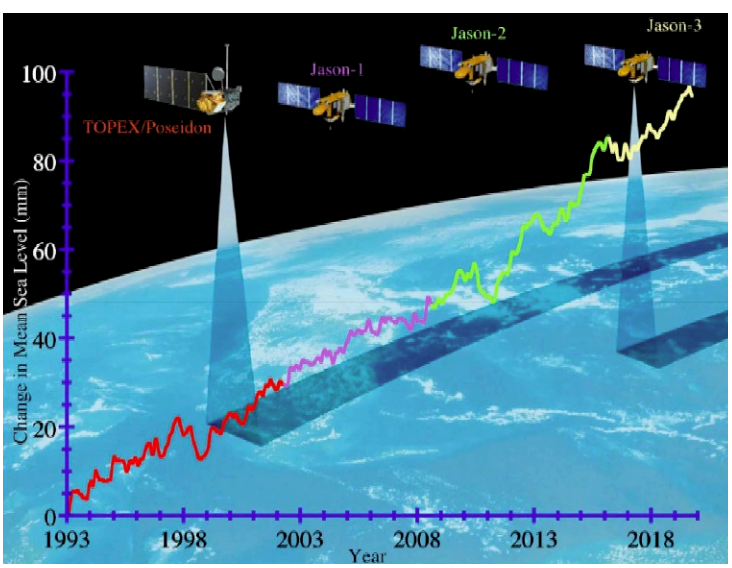

Figure 3. *Sea-level graph*. The graph shows global mean sea-level variations over the entire length of the satellite altimetry time series, which begins in 1993 with TOPEX/Poseidon and continues uninterrupted to the present day with the overlapping missions of Jason-1, -2, and -3. Note that sea level has trended upward over the past three decades. This record should continue well into the future with the upcoming launches of the Sentinel-6 Michael Freilich (2020) and Sentinel-6B (2025) missions. **Image credit:** R. Steven Nerem

Table. Science focus-area presentation topics, speakers, and summaries (*continued*).

Topic	Speaker [Affiliation]	Presentation Summary
Ocean Imprints: Air–Sea Interaction from Space	**Carol Anne Clayson** [WHOI]	Discussed satellite studies of air–sea coupling—an area where Mike played a pioneering role.* Described how surface temperature and unfiltered wind speed have been conclusively shown to be negatively correlated at large scales. In the past two decades, work has focused on increasingly smaller scales where it appears that the ocean may contribute strongly to atmospheric forcing rather than being passively responsive. The future in this area is to observe air–sea fluxes at even higher resolutions to develop a full picture of air–sea interaction at sub-100-km (-62-mi) scales. Mentioned S-MODE, an Earth Venture Suborbital mission to study the role kilometer-scale ocean eddies play in vertical exchange of climate and biological variables in the upper ocean.
The Howling Fifties: Wind Forcing of the Southern Ocean	**Sarah Gille** [Scripps Institution of Oceanography]	Discussed the challenge of collecting *in situ* observations in the Southern Ocean (SO) and how this provided an opportunity to test satellite scatterometry in the 1990s. NSCAT was the first mission to observe winds from space, followed by QuikSCAT, RapidScat, and other international missions. Early observations over the SO revealed the impact that South Georgia Island has on wind flow and that storms in the region occur roughly once a week. Recently, the focus has been on determining where and when these storms occur. Explained how storms generate waves, analogous to the impact a pebble has on a pond. Showed statistics describing how satellite observations have improved wind-forcing observations over the SO.
Advances in Measuring the Tiniest Amounts of Water in Air	**Graeme Stephens** [JPL—*CloudSat PI*]	Discussed studying clouds from space. Commented that often we think of Earth as a (or *the) blue planet*, but we could think of it as a *white planet*, since much of Earth is always covered by a "thin white veil," as he put it, in the form of clouds. We can measure the variation in *whiteness* in different ways using CloudSat and CALIPSO. Of all the reservoirs on our planet (ocean, atmosphere, cryosphere, land), land is least understood. For example, we still don't know how much fresh groundwater exists and is available for use. Much of current Earth science research focuses on understanding and quantifying the exchanges between these main water reservoirs. Used the example of sea-level rise to illustrate why such tiny amounts of water are so important: Warming drives sea-level rise—and clouds dramatically impact warming.
Monitoring Polar Regions in 4D	**Thorsten Markus** [NASA HQ—*Cryospheric Science Program Manager*]	Discussed polar ice studies from space, which began about 40 years ago with passive microwave observations. While these data provided information on the extent of the sea ice, *thickness*—an important datum—had to be approximated. Noted that it was "under Mike's tenure that the *z-dimension* (i.e., thickness) has truly been added to polar ice studies." ICESat (2003–2009) operated in short campaigns, but ICESat-2 (2018–present) has—for the first time—enabled year-round maps of sea-ice thickness. Also under Mike's tenure, Operation IceBridge was established, which bridged the two ICESat missions with aircraft flights. Looking to the future, NISAR (planned for 2022 launch) will allow the next step in sea ice studies; it will measure ice mass velocity from space. Showed an animation of InSAR (aircraft) ice-mass velocity data over Greenland.
Getting Wet with Precipitation Science	**Gail Skofronick-Jackson** [NASA HQ—*GPM Program Scientist*]	Discussed the evolution of satellite precipitation measurements. TRMM (1997–2015) provided the first radar precipitation measurements from space, followed by GPM (2013–present), which provides wider coverage than TRMM. Discussed all the partner sites where ground-based measurements are being taken for GPM, noting that Mike played important roles in developing these international partnerships. Mentioned field campaigns, which are used to validate GPM data. There was a segment on National Public Radio's *All Things Considered* about the IMPACTS campaign—the first campaign to look at U.S. East Coast snowstorms in 30 years.** Showed the latest IMERG global map of precipitation. Discussed applications derived from TRMM and GPM data. Showed combined data from the TEMPEST-D and RainCube CubeSat missions—see **Figure 4** on page 11—both of which demonstrated technologies for future missions, e.g., TROPICS (Earth Venture), and ACCP (combines two Designated Observables identified by the 2017 ESDS).

footnotes and acronyms on next page

‡ Sentinel 6/Jason-CS consists of two identical missions, Sentinel-6A, planned launch in 2020, and Sentinel-6B, planned launch in 2025. On January 28, 2020, Sentinel-6A was officially renamed Sentinel-6 Michael Freilich. For details, see the Editorial in the January–February 2020 issue of *The Earth Observer* [**Volume 32**, **Issue 1**, pp. 1-2].

* Dudley Chelton's keynote presentation discusses this phenomenon in detail.

** The podcast is available at *https://go.nasa.gov/2x5f2yT*.

List of Undefined Acronyms Used in Table

ACCP—Aerosol and Cloud, Convection, and Precipitation

CALIPSO—Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations

CZCS—Coastal Zone Color Scanner

GRACE—Gravity Recovery and Climate Experiment

GOCE—Gravity Field and Steady-State Ocean Circulation Explorer

GPM—Global Precipitation Measurement

ICESat—Ice, Clouds, and land Elevation Satellite

IMERG—Integrated Multi-satellitE Retrievals for GPM

IMPACTS—Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms

InSAR—Interferometric Synthetic Aperture Radar

MODIS—Moderate Resolution Imaging Spectroradiometer

NSCAT—NASA Scatterometer

PACE—Plankton, Aerosol, Cloud, and ocean Ecosystem

QuikSCAT—Quick Scatterometer

RapidScat—Rapid Scatterometer

S–MODE— Sub-Mesoscale Ocean Dynamics Experiment

SeaWiFS—Sea-viewing Wide Field-of-view Sensor

TEMPEST-D—Temporal Experiment for Storms and Tropical Systems-Demonstration

TOPEX—Ocean Topography Experiment

TROPICS—Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats

TRMM—Tropical Rainfall Measuring Mission

VIIRS—Visible Infrared Imaging Radiometer Suite

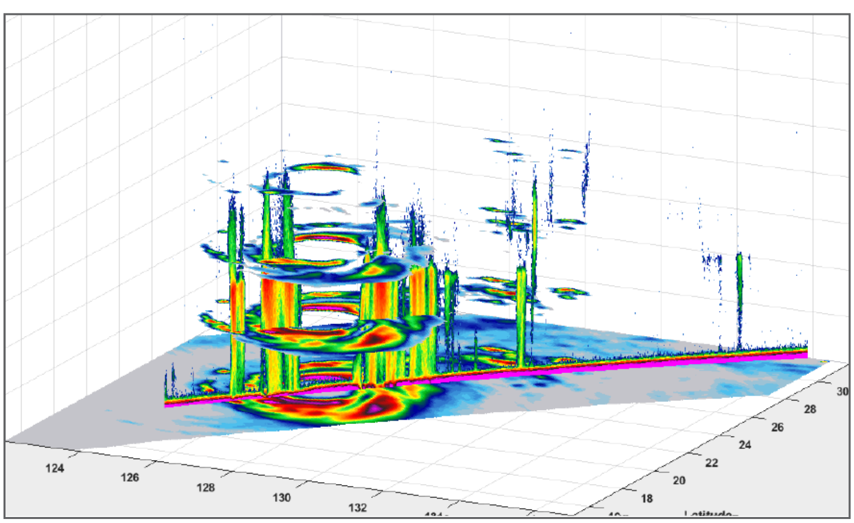

Figure 4. *CubeSats view Typhoon Trami.* On September 28, 2018, two CubeSats flew over Typhoon Trami off the southern coast of Japan shortly after it had weakened to a Category 2 storm. Separated in time by less than five minutes, the RainCube nadir K_a-band reflectivity (vertical peaks) is shown overlaid on TEMPEST-D 165-GHz brightness temperature (horizontal layers). Combining data from these two storms gives an informative picture of the three-dimensional structure of the hurricane. **Image credit**: Gail Skofronick-Jackson

Science Focus Area Panel Discussion

After all presentations in this session were complete, the speakers returned to the stage as a panel—see photo below—to take questions from the audience. While the sheer amount, the wide range, and the detailed nature of this discussion makes it impossible to fully present the whole discussion in this article, the most pertinent information appears below. The full dialogue begins at 5:06:06 of the livestream—*https://go.nasa.gov/395OieG*.

Colleen Hartman served as moderator for this dialogue, and asked the first question: *What new observations would be most helpful?* **Graeme Stephens** said, "Earth is a dynamic system—constantly changing and evolving—and we have to capture the essence of its dynamics." **Byron Tapley** mentioned the need to replicate measurements currently made from polar orbit from geosynchronous orbit—which allows continuous monitoring as opposed to being limited to one or two overpasses a day. Beyond this, simply being able to fund more instruments would be helpful. Specific to ocean disciplines, **Paula Bontempi** said ocean-penetrating lidar is needed. For precipitation studies, **Gail Skofronick-Jackson** mentioned that more observations in the planetary boundary layer would be valuable.

The eight Science Focus Area presenters took questions from symposium participants on a range of topics, with **Colleen Hartman** [*standing at podium*] serving as moderator. The presenters, all identified in the Table on pages 9-11, were [*from left to right*]: **Gail Skofronick-Jackson**, **Paula Bontempi**, **Sarah Gille**, **Graeme Stephens**, **Thorsten Markus**, **R. Steven Nerem**, **Carl Anne Clawson**, and **Byron Tapley**. **Photo credit:** The National Academies of Sciences, Engineering, and Medicine (NASEM)

Lee Leung Fu [JPL] asked about the *future path for detecting extreme events*. Skofronick–Jackson commented that GPM is already doing some of this: e.g., susceptibility to fires, floods, and landslides. She noted that, at least with precipitation, we know where extremes are happening now, but predicting the future is where we need to improve. Stephens added that from a pure monitoring perspective, observing extremes is hard. However, we can connect data to prediction systems, leading to advances in modeling.

Randy Friedl [JPL] asked more of a "big picture" question. He noted that the old days, e.g., the pre-EOS era, were characterized by lots of exploration, discovery, and empiricism, but he asked: *Is there any sense of those qualities in our research today?* In response, Tapley commented that NASA and its domestic and international Earth science partners have amassed terabytes (soon to be petabytes) of data and have assimilated them into models. But progress is still needed to connect those data with the end-users who need it to study various environmental phenomena. Stephens reminded everyone that models represent "an articulation of what we understand"—i.e., they aren't how the "real world" works, so there's still much we need to discover. **Carol Anne Clayson** added that, for oceanography, observation is expensive—but there's still plenty to discover; others concurred with this assessment for their respective disciplines.

Paula Bontempi's *advice was: Whatever you are doing, learn to say, "no, I can't do it" if time and/or resources don't permit you to do it, and also not to precede it with an apology or follow it with an excuse.*

Sandra Cauffman [NASA HQ—*Acting Director of NASA's Earth Science Division*] asked about *advice for young scientists*. **Paula Bontempi's** advice was: Whatever you are doing, learn to say, "no, I can't do it" if time and/or resources don't permit you to do it, and also not to precede it with an apology or follow it with an excuse. She also suggested they learn to stick with those assignments you do accept, saying that "in [my] experience, life is 90% test of will, 10% smarts." Stephens added that young scientists should always be willing to question the prevailing assumptions about how things work—because they may be correct, despite being different from accepted norms. He continued by saying that investigators should always be driven by a desire to understand. They also need an immense amount of *imagination*—a capacity that cannot be coached or earned with a degree. Skofronick-Jackson's advice was to look for inspiration in unexpected places. For example, she took a class in public policy as an engineering student and saw a hurricane photo in class, which got her curious about remote sensing; the rest is history. **Steve Nerem** said that to be successful, you have to be able to "sling data." Therefore, his advice is that young scientists get comfortable with computers and crunching numbers. **Thorsten Markus** added that so much innovation comes from young scientists; they should not be discouraged by an older scientist saying, "it can't be done."

Bruce Wielicki [NASA's Langley Research Center (LaRC)] commented that we have had an international weather observing system for many years. He asked: *Why is there no true international climate observing system? What can we do to bring this about?* Bontempi said that we haven't really put in place the infrastructure to have such a group capacity—although she thinks we've made progress in the past couple of decades—particularly under Mike's leadership. Stephens added that the "thousand-pound gorilla" is often: "How can we afford this?" **Mike Freilich**, as he did so often during his time at NASA, countered with: "Can we afford *not* to do it?" In other words, if we decide this needs to be a priority, then we must work on crafting the arguments to make it happen.

__Graeme Stephens__ added that the, "thousand pound gorilla" is often: "How can we afford this?" __Mike Freilich__, as he did so often during his tenure at NASA, countered with: "Can we afford not *to do it?"*

Carol Anne Clayson ended this discussion by stating that last week (January 16–20, 2020) at the American Meteorological Society's Annual Meeting in Boston, MA, Senator Sheldon Whitehorse [RI] noted that tactics used by those opposed to enacting policy to combat climate change are similar to those used by the tobacco lobby. When the secondhand impacts of smoking became evident, progress was possible; the same may be true with climate change. If enough people better understand the long-term impacts climate change is having on Earth's systems—and its potential impact on future generations—then the world might see more significant action on such change. Stephens agreed, and said, "I think *we* can craft that story—and that the time is right to tell it," and the people at this meeting are some of the most capable people in the world to tell it convincingly.

Panel on Strategies for Program Implementation

Sandra Cauffman moderated this panel. Each panelist discussed his or her specific working relationship with Mike, the leadership he provided for the Earth Science Program, and the lessons he or she learned under his leadership. Summaries of these discussions are provided here. This discussion begins at 5:32:36 of the livestream.

Jack Kaye [NASA HQ—*Associate Director for Research and Applications of the ESD*] spoke from the perspective of the ESD, as someone who worked for Mike at NASA HQ. He said that NASA's ESD is a unique *end-to-end* effort, i.e., it makes observations, collects data, applies algorithms, validates, archives, interprets, and conducts science and applications. He also spoke of the importance of NASA working with and being responsive to the needs of the broader Earth science community. In addition, the agency operates in a global context, so NASA must work together with domestic and international partners to accomplish mutual goals. Furthermore, it is necessary to think of how the policies enacted and programs planned impact the people involved. Kaye said he has learned a lot about working with people from Mike. He ended with a piece of advice Mike gave him, which was: "Don't half-solve problems."

Mark Abbott [WHOI—*Director*] spoke from the perspective of a representative of a research institution interacting with Mike as head of the ESD. He mentioned an email from Mike in 2003, in which he gave Abbott and others some advice on how to develop and implement a program, saying it has to be "doable, measurable, and sustainable." During his career, Abbott and others he worked with have had to figure out how to hire the right people and create the right environment for them to succeed. He noted that Mike was very good at doing this. Also, as stated in earlier discussion, Abbott commented that Mike "moved from 'desirements' to requirements," i.e., he thought deeply about *what* NASA wanted to do and didn't confuse that with *how* it would be done (e.g., which often came down to *how* the idea could be funded). He also discussed how Mike always emphasized the need to evaluate lessons learned. Mike had strong opinions and didn't hesitate to share them—but the words he spoke always provoked deeper thinking on the subject. Echoing Paula Bontempi's earlier statement, Abbott said: "We came to a better solution because Mike was in the room." Sandra Cauffman concurred that she had similar experience working with Mike. She used an academic analogy to describe how Mike communicated: She frequently got the sense that he was saying to her, and sometimes to all of NASA: "You're getting a C, but you are capable of an A!"

Sandra Cauffman *used an academic analogy to describe how Mike communicated: She frequently got the sense that he was saying to her, and sometimes to all of NASA: "You're getting a C, but you are capable of an A!"*

Pamela Whitney [U.S. House of Representatives, Subcommittee on Space and Aeronautics—*Staff Member*] spoke from the perspective of a NASA stakeholder. She talked about her interactions with Mike in forming NASA's response to plans to implement the first (2007) ESDS.[9] She described the resulting document as a comprehensive overview of what it takes to actually implement a program. It tells a compelling story of how all these different measurements come together to contribute to the overall theme of understanding Earth's changing climate. Mike used this report as his "report card" or "progress report" for NASA. Whitney thought that it was an excellent example of how having a strategic plan helps all parties involved work together to reach a common goal. Cauffman commented that pertinent communities are, in a sense, "starting over again," creating a similar document to formulate NASA's response to the second (2017) ESDS.

Ed Kearns [U.S. Department of Commerce] spoke from the perspective of partner organizations working with NASA. He focused on his interactions with Mike when Kearns was a program examiner at the Office of Management and Budget (OMB). He said that Mike was good at leading scientists through adversity to a successful outcome. Kearns tries to put in practice things he learned from Mike, noting that PhD programs don't tend to teach us how organizations run; one has to learn this on the job. A successful program needs competent scientists to lead it and to cast a vision—and Mike provided both leadership and vision for NASA's ESD. Cauffman added that Mike was always good at earning trust from those he worked with.

After the panelists spoke, there was a short window for questions. Cauffman asked: *What were the most noteworthy accomplishments for the ESD under Mike Freilich?* **Jack Kaye** answered, "All things Decadal Survey." For example, the Designated Observable concept that is an integral part of the second ESDS is a new idea that Mike championed. Kaye also mentioned the climate-centric architecture of the second ESDS. **Mark Abbott** talked about how Mike responded to failure, in that there were several launch failures during Mike's tenure as director of ESD (e.g., OCO, Glory). Abbott noted that NASA always thoroughly investigated and sought to learn from its failures and added that learning from failure is key to a successful organization. **Pam Whitney** expanded on that, stating that Mike has a very open thought process. He was always open to doing it new ways, which is evident in the current NASA Earth Science *Program of Record*[10]—e.g., observations from the ISS, hosted payloads, small satellites, and partnerships. **Ed Kearns** said that Mike excelled at filling gaps in the observing system. For example, he pursued QuikSCAT to replace the unexpected failure of NSCAT, and then negotiated to keep it going even after the antenna stopped spinning, so it could be used to provide calibration information for other nations' scatterometers. Kearns also said that Mike always, "kept it human," i.e., he realized that schedules can—and will—"slide to the right," and that people were more important than progress.

Panel on International Collaborations

Ernesto Rodriguez [JPL] moderated this panel, made up of representatives from NASA's international partners. Each panelist spoke about his or her organization's relationship with NASA—and his or her personal connections with Mike. Rodriguez shared some memories of his interactions with Mike during negotiations with the

[9] The document can be found at *https://go.nasa.gov/2xbT0u1*.
[10] *Program of Record* is the term the second ESDS uses to refer to current NASA Earth observations, as well as those already in formulation—i.e., those that will be implemented regardless of whether any recommendations from the second ESDS are implemented.

Indian Space Research Organisation (ISRO) over continuing scatterometry measurements after QuikSCAT's antenna stopped spinning in 2009. Mike helped Rodriguez navigate the negotiations and secure agreements that extended the winds dataset for an additional decade. This discussion begins at 6:01:01 of the livestream.

Maurice Borgeaud [European Space Agency (ESA)] showed the European "Taking the Pulse of the Planet" globes, showing the different environmental measurements that ESA satellite missions make. To frame his remarks on NASA–ESA cooperation in Earth observations, he referred to a quotation from Henry Ford: "Coming together is a beginning; staying together is progress; and working together is success." Borgeaud discussed collaboration in three broad areas: flight missions; field campaigns and analysis; and data portals, archives, and standards. He then showed examples in each of these areas of collaboration. Throughout his presentation, Borgeaud interweaved memories of personal interactions with Mike.

Coming together is a beginning; staying together is progress; and working together is success.
—Henry Ford [quoted by Maurice Borgeaud]

Selma Cherchali [Centre National d'Études Spatiales (CNES)] reviewed the history of NASA–CNES cooperation, which includes collaboration in the fields of altimetry, geodesy, and atmospheric science (clouds/aerosols). With regard to altimetry, the partnership dates back to 1983—when Mike was working at JPL, as described in Dudley Chelton's keynote presentation on page 5. She noted that Mike played a key role in this joint venture in satellite altimetry over the years. Looking to the future, Cherchali discussed the upcoming SWOT mission, referring to it as "a CNES water dream come true." She mentioned three qualities that characterize the NASA–CNES partnership: building trust, valuing diversity, and commitment to a common vision, and then elaborated on each of these areas.

Chu Ishida [Japan Aerospace Exploration Agency (JAXA)] discussed U.S.–Japanese collaboration on Earth observations—which goes all the way back to ADEOS (NSCAT) and ADEOS-II (SeaWinds). As a specific success story, he discussed the GPM mission, as well as cooperation on the JAXA Greenhouse Gases Observing Satellite (GOSAT) and NASA Orbiting Carbon Observatory (OCO) missions. Ishida also mentioned future collaborations on climate studies, which he described as "crucial to the future of our planet."

Rodriguez concluded this panel by reading a letter written to Mike from **Alain Ratier** [European Organization for the Exploitation of Meteorological Satellites (EUMETSAT)—*Director General*], who was unable to attend in person. In his letter, he spoke fondly of his interactions with Mike, saying that, "[Mike] proved to be a highly committed, dependable, and intelligent partner, even in the most difficult circumstances that are unavoidable in complex cooperation. [His] unique leadership style combining patience, resilience, humor, and solid judgment was decisive for the success of cooperation."

At the end of this panel, each of the three speakers presented Mike with gifts on behalf of their respective organizations—see photo [*right*].

Chu Ishida presents **Mike Freilich** with a framed certificate, with **Maurice Borgeaud** watching. Each of the international collaborations panelists presented Mike with a gift from their respective organizations. **Photo credit:** NASEM

Panel on New Directions

Chelle Gentemann [Farallon Institute, Earth and Space Research] chaired this session, which focused on exciting new advances in science that Mike enabled as ESD director. The presentations in this section highlighted new interdisciplinary and open ways of doing science, new ways of looking at data, and innovative ways of looking at the Earth system. This discussion begins at 7:14:51 of the livestream.

Clarissa Anderson [Scripps Institution of Oceanography, Southern California Coastal Observing System] showed the phenomenon known as *the Blob*—a warm anomaly in the central Pacific Ocean in 2015, which caused a toxic harmful algal bloom (caused by a diatom called *Pseudo-nitzschia*). The diatom produces a neurotoxin called *domoic acid* that severely impacted the ecosystem and economy (e.g., the Dungeness crab fishery was closed for a year). She discussed how she and her colleagues used ocean-color imagery and models to track harmful algal blooms, creating the California Harmful Algae Risk Mapping (C-HARM) system to forecast domoic acid risk.[11] Anderson ended by saying that the "holy grail" of their research quest is to identify the optical signature of specific neurotoxins, e.g., domoic acid, as ground-based observations have shown that water looks different when the toxin is present. Her team is hopeful that data from NASA's Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) mission will provide a "hyperspectral revolution," and help them take the next step in their studies.

Cecile Rousseaux [NASA's Goddard Space Flight Center/Goddard Earth Science Technology and Research (GESTAR)/Universities Space Research Association (USRA)] discussed the impact of the ocean on Earth's carbon cycle. Globally, the ocean acts as a sink of carbon dioxide, thereby reducing an increase in atmospheric carbon dioxide. There are two ways the ocean absorbs carbon: the *dissolution pump* and the *biological pump.* She focused on the biological pump, going into detail on how it works, and highlighting the need for an interdisciplinary approach to quantify the various components involved in the cycle. Rousseaux discussed the effects of climate variability on oceans, showing the ocean color data animation that shows Earth "breathing"—see Paula Bontempi's presentation summary in the Table on page 9. Rousseaux ended by discussing plans for using PACE to obtain this kind of data.

*In his closing remarks, **Miguel Román** made a call-to-action for greater commitment, flexibility, and vision to proactively involve science and civil society in developing all aspects of disaster response, aid, and resilience.*

Miguel Román [Earth from Space Institute/USRA] discussed the role of Earth scientists as advocates to help address priority needs in managing climate change and disaster risk. He focused on the specific context of Puerto Rico's recent (January 2020) earthquakes. He said that the last two years have been particularly difficult for Puerto Rican communities, recognized as some of the poorest and most underserved citizens of the U.S. He showed results using NASA's Black Marble "Nighttime Lights" product, which illustrates how Puerto Rico looked before and after the magnitude-6.4 earthquake and subsequent aftershocks. The events caused significant damage to homes, buildings, roads, and other critical infrastructure. Román mentioned that there is a *memory effect* to these disasters, noting how communities previously affected by Hurricanes Irma and Maria were more likely to undergo longer periods without access to electricity and other basic services than those the two hurricanes had not impacted. His results also showed that, owing to Puerto Rico's outdated centralized electricity infrastructure, power outages were more widespread than structural damage. Román pointed out that Puerto Rico is also the place in the U.S. most impacted by energy insecurity, which makes it an ideal proving ground for energy-efficient and renewable-energy technologies. In his closing remarks, Román made a call to action for greater commitment, flexibility, and vision to proactively involve science and civil society in developing all aspects of disaster response, aid, and resilience.

Ryan Abernathy [Columbia University, Lamont–Doherty Earth Observatory] opened with the question: *What drives progress in Earth science?* He mentioned ideas, observations, and simulations (models). When it works well, there are flows between these three areas but—owing to the increasing size and complexity of contemporary datasets—these flows have been breaking down. To give a concrete example, he showed an animation of how the resolution of satellite altimetry data has improved over time—including a projection of what the addition of SWOT could allow in the future. The increase in resolution over time comes with an exponential increase in the amount of data to process, which presents its own challenges. Next, Abernathy asked: *What*

[11] C-HARM is used to create daily nowcasts and three-day forecasts of domoic acid risk through simulations of ocean physical circulation; it uses a Regional Ocean Model System (ROMS) to predict water temperature, salinity, upwelling, and advection.

do scientists want to do with satellite data? He focused his response on spatiotemporal statistics, machine learning, and data assimilation. These methods require all the data to be available. The old model, based on downloading data to a personal computer, simply doesn't work for the data volumes of the 2020s. So, the new approach is to use a *platform* to bring the computing to the data, rather than the reverse. But even a platform approach has limitations, which Abernathy described. He said that a *data refinery* is needed—to take crude data (like crude oil) and extract the different types of information desired. He then described the *federated cloud architecture* approach, which brings data and computing together in the same place. As a specific example, he also discussed *Pangeo* (*https://pangeo.io/about.html*)—a community platform for so-called "big data" processing—and described its architecture, which includes open-community/open-source software, and open-community structure. The idea is to build a complete computing environment in the cloud that users can connect to via web browsers. Abernathy said this new technology has the potential to transform Earth science, and then ended his presentation by listing some challenges that must be overcome to make this happen.

Drew Bollinger [Development Seed] described how open-source data are being used to tackle humanitarian or social-good problems, e.g., live mapping of roads in the Philippines, and finding electricity infrastructure in Pakistan. Bollinger also mentioned collaboration with NASA SERVIR[12] (*https://www.nasa.gov/mission_pages/servir/index.html*) whose mantra, "bringing space to village," meshes perfectly with the mission of Development Seed. He described the work Development Seed does with the IMPACT[13] team at NASA's Marshall Space Flight Center on the Deep Learning-based Hurricane Intensity Estimator, which can predict hurricane intensity by looking at overlaid satellite imagery (e.g., GOES images). Bollinger said Development Seed is helping to "bring distributed active archive center processing into the cloud." This method allows one to effectively scan in all (or large amounts of) relevant imagery and search for hazards or other phenomena of interest. Development Seed hopes to apply these data-processing techniques to study other atmospheric phenomena in the future.

***Chelle Gentemann** repeated something that Mike often emphasized: that the global challenge of climate change requires a global response.*

Earth Science and Applications from Space: Summary

Chelle Gentemann summarized the day and showed beautiful images of our planet from space and animations of models and data that Mike's stewardship has enabled. She said that Mike was able to capture and convey science in a lighthearted but effective way that pushed Earth system science forward, in the process creating strong international collaborations. Gentemann repeated something that Mike often emphasized: that the global challenge of climate change requires a global response. New technology and new ways of enabling collaborations through open science will build on the foundation that Mike has built and will propel science forward to address the challenges we face from climate change.

In her closing remarks, **Colleen Hartman** echoed Gentemann's thanks to all who were involved in making the Symposium a reality. In particular, she thanked the Freilich family, especially Mike's wife Shoshannah, and Mike's mother and children, for being here on this special day. She also thanked her fellow Symposium organizers, who "did a marvelous job with the program and were a delight to work with." Finally, she thanked the staff from the NASEM Space Studies Board for their contributions.

Concluding Comments from the Guest of Honor

It was only fitting that Mike should have the last word at the Symposium held in his honor—at 8:21:08 of the livestream. "I'm *really* happy to attend today," he said as he began his remarks. He once again thanked the organizing committee, sponsors, and—last but not least—the speakers—saying that "*you* provided the substance

[12] SERVIR is not an acronym; it is a Spanish word that means "to serve."

[13] IMPACT stands for Interagency Implementation and Advanced Concepts Team (*https://earthdata.nasa.gov/esds/impact*). This should not be confused with the IMPACTS field campaign, discussed earlier in this article.

Mike Freilich—the symposium's guest of honor—gave the final presentation of the afternoon. He reflected on his accomplishments while at NASA and expressed his thanks for the opportunity to be part of this event—and for the privilege of being part of NASA for so many years. His remarks were a fitting end to a day of shared memories and tributes to a man whose distinguished career left an indelible impact on the Earth science community—and on NASA's Earth Science Division in particular. **Photo credit:** NASEM

of the Symposium." Mike thanked all who participated—including those listening online. He spoke with justifiable pride about how, under his watch, the U.S. Earth science community moved from an inward-focused, or "tribal," approach to studying Earth, with individual disciplines studying particular components of the Earth System independent from one another, toward a much more outward-focused approach of studying Earth as an integrated system with interrelated components—a.k.a., a *system of systems*. With each of the ESDS reports providing a "roadmap," the Earth science community has come together to study Earth's changing climate.

Mike mentioned the crucial role international collaboration has played in enabling studying the Earth as a system of systems—and in studies of global climate change in particular—which has been elaborated on at this symposium. He said that international partners are now truly equal partners. As an example, he cited the SMAP mission, which he called a great example of "true and deep international collaboration—and *you* [this time referring to the wider Earth science community] have helped bring it about." He also talked about how international collaborations have expanded to include the full spectrum of Earth science activities—i.e., not just developing flight hardware.

"The life of the individual only has value in so far as it aids in making the life of every living thing nobler and more beautiful."
—*Albert Einstein* [quoted by Mike Freilich]

Mike once again expressed his thanks for the opportunity to be part of this Symposium—and the privilege of being part of NASA for so many years. He shared a quote from Albert Einstein: "The life of the individual only has value in so far as it aids in making the life of every living thing nobler and more beautiful." While Einstein used the quote in a different context, Mike felt that it also applied to the context of this symposium. He said, "The work that *you* do contributes to making the life of every living thing nobler and more beautiful." He ended by thanking his wife and family for the tireless support they offered him throughout his career—and particularly during his tenure as director of NASA's ESD. Mike received a standing ovation at the end of his remarks, a fitting finale to a day of shared memories and tributes to a man whose distinguished career has left an indelible impact on the Earth science community—and on NASA's ESD in particular. ■

Summary of the 2019 South/Southeast Asia Research Initiative Land Cover Land Use Change Regional Science Meeting

Krishna Prasad Vadrevu, NASA's Marshall Space Flight Center, krishna.p.vadrevu@nasa.gov
Kasturi Kanniah, University of Technologi, Malaysia, kasturi@utm.my
Tsuneo Matsunaga, National Institute for Environmental Studies, Japan, matsunag@nies.go.jp
Chris Justice, University of Maryland, College Park, cjustice@umd.edu
Garik Gutman, NASA Headquarters, ggutman@nasa.gov

Introduction

As a result of growth in South and Southeast Asia (S/SEA), land use/cover change (LUCC) is occurring at a rapid rate, moving from forest to agriculture and from agricultural areas to residential and urban use, with concomitant disruption of water and forest resources, biodiversity, regional climate, biogeochemical cycles, and the atmosphere. To address these issues, NASA's Land Cover/Land Use Change (LCLUC) Program—South/Southeast Asia Research Initiative (SARI, *www.sari.umd.edu*) in collaboration with other partners organized a meeting, titled *Land-Use/Cover Changes, Environment and Emissions in South/Southeast Asia*, held July 22–24, 2019, at the Hilton Hotel in Johor Bahru, Malaysia. The University of Technologi, Malaysia (UTM) hosted the meeting. Collaborators included the National Institute for Environmental Studies (NIES), Japan; the international Global Observations of Forest and Land-Use Dynamics (GOFC–GOLD) program; START,[1] U.S.; and the international Group on Earth Observations Global Agricultural Monitoring (GEOGLAM) initiative, in addition to fourteen other national and international partners. The meeting aimed to review the availability, potential, and limitations of different satellite data sources and methodologies for monitoring LUCC, and its impact on the environment. Another objective was to strengthen GOFC–GOLD S/SEA regional networks on the latest LUCC science.

[1] START (not an acronym) is a core international partner of the U.S. Global Change Research Program that seeks to realize a sustainable future through science (*https://start.org*).

The three-day meeting was attended by 170 participants from 16 countries—see **Photo 1** below.

After several opening presentations, the bulk of the meeting was organized into five sessions, including:

- Updates on Regional Programs and Space Agency Activities;
- Agricultural LUCC;
- Land–Atmosphere Interactions and Emissions;
- Forest LUCC; and
- Urban LUCC.

In addition, on the final day of the meeting there were three discussion sessions that focused on regional research and priorities for agriculture, atmosphere, and LUCC capacity-building themes.

The remainder of this article is organized by day and presents highlights from each of the sessions and the discussions. It also includes a brief description of a press conference held on the afternoon of the first day, to introduce the local media to the practical applications of LUCC science, and a three-day, hands-on training event that took place immediately after the SARI LCLUC meeting, which focused on the use of remote sensing and geographic information systems for LUCC applications. The reader is directed to *https://go.nasa.gov/3a4NtUK* to find more information about the meeting, including the full presentations.

Photo 1. SARI LCLUC regional science meeting participants in Johor Bahru, Malaysia. **Photo credit**: University of Technologi Malaysia (UTM) team

DAY ONE

The first day began with opening remarks to put the meeting in perspective. The remainder of the day was used for a series of presentations from SARI international partners, describing the status of the remote sensing activities of each nation represented—particularly as it relates to LUCC studies. The last two sessions of the day (each with four presentations), on Agricultural LUCC as well as Land–Atmosphere Interactions and Emissions respectively, set up the parallel sessions on each of these topics that would follow on day two. There was also a press conference that took place on the first day—see *The Local Media Learn the Importance of Land Use/Land Cover Science* on page 21.

Opening Remarks

The meeting began with welcoming a series of opening presentations. Speakers included **Kasturi Kanniah** [UTM, Malaysia—*Professor, Built Environment and Surveying*], **Garik Gutman** [NASA Headquarters (HQ)—*LCLUC Program Manager*], **Chris Justice** [University of Maryland, College Park (UMD)—*LCLUC Program Scientist*], **Krishna Vadrevu** [NASA's Marshall Space Flight Center (MSFC)—*SARI Project Lead*], and **Tsuneo Matsunaga** [NIES—*Greenhouse Gases Observing Satellite (GOSAT) Lead*]. All emphasized the need for strengthening international collaboration on LUCC science and building more projects involving U.S. and SARI regional scientists.

Updates on Regional Programs and Space Agency Activities

Garik Gutman presented the latest updates on NASA's LCLUC Program and research activities in S/SEA. He showed that since 2015, more than 25 projects have been funded as a part of the SARI initiative through NASA's LCLUC Program and that the related meetings, workshops, and training activities are strengthening the research and collaborations in S/SEA. He highlighted important LUCC issues in the region, including the loss of agricultural land due to urban expansion, slash-and-burn agriculture impacts on air quality, and the expansion of aquaculture, roads, dams, and mines resulting in the loss of natural habitat. Air quality in several cities of S/SEA is a major concern, as fine particulate matter ($PM_{2.5}$) levels exceed the World Health Organization (WHO) established limits. Further, smoke from slash-and-burn clearing of forests causes transboundary haze that impacts visibility and exacerbates human health concerns in Malaysia, Singapore, and southern Thailand. Satellite instruments from NASA and the European Space Agency (ESA) have been effective tools for following such phenomena, along with a decrease in mangrove forest cover in SEA. Gutman described an increase in such forest cover along the southern coast of Thailand, due to aggradation (deposition from rivers). He stressed the need for strong collaborations in research capacity building and training activities in SARI countries.

Prakash Chauhan [Indian Institute of Remote Sensing (IIRS)] highlighted the operational remote sensing satellite missions of the Indian Space Research Organization (ISRO), along with some of their technical characteristics, emphasizing improvements and overlaps. Chauhan mentioned that most of the data from ISRO missions are useful for planning, monitoring, evaluating, and providing decision support in LUCC. Satellite-based weather and ocean data are available from ISRO's Meteorological & Oceanographic Satellite Data Archival Centre (MOSDAC; *https://www.mosdac.gov.in*), while the land-based data are available from ISRO's Geo-Platform—called *Bhuvan*.[2] Chauhan also mentioned that the IIRS is involved in training and education programs.

Lam Dao Nguyen [Vietnam National Space Center (VNSC)] provided details on the ongoing space activities in Vietnam. He stated that data from the Vietnam Natural Resources, Environment and Disaster Monitoring Satellite (VNREDSat-1), launched in 2013, are used for forest mapping, land, urban, and water management studies. Also, VNSC has been using ESA's Copernicus Sentinel-1 and Canadian RADARSAT (1995–2013) data for forest cover observations and for rice mapping and monitoring, including flood detection, in Vietnam. In addition, under the Committee for Earth Observations (CEOS) activities, a data cube is being developed integrating data from several NASA and ESA platforms for forest and rice monitoring studies.

Rokhis Khomarudin [National Institute of Aeronautics and Space,[3] Indonesia] presented updates on the LAPAN space remote sensing activities, noting the ongoing success of the LAPAN-A3 satellite, which was launched in June 2016 to be used for LUCC studies. The LAPAN project also receives data from many NASA and ESA satellites through their ground stations. These datasets are routinely used for mapping forest cover, mining activities, industrial areas, and paddy-growth monitoring.

Gay Perez [University of the Philippines] provided details on Philippine space remote sensing activities. Two important satellites currently on orbit include DIWATA-1 (D-1) and DIWATA-2 (D-2).[4] D-1 was launched in April 2016 and D-2 in October 2018. D-1 already exceeded its estimated lifespan of 18

[2] Bhuvan is a web-based utility which allows users to explore a set of map-based content prepared by the Indian Space Research Organisation. It can be accessed at *https://bhuvan.nrsc.gov.in/bhuvan_links.php*.

[3] In Malaysian, this is Lembaga Penerbangan dan Antariksa Nasional (LAPAN).

[4] This is not an acronym: In Philippine mythology, a *Diwata* is a type of deity or spirit. The platform is also called PHL Microsat-1.

months whereas the D-2 estimated lifespan is 3-5 years. Both these satellites have a high-precision telescope, a spaceborne multispectral imager, and an enhanced-resolution camera. D-1 and D-2 have already captured just over a third of the Philippine land area and the data are mostly used for vegetation change assessment, post-typhoon damage assessment, monitoring built-up areas, and delineating landslides. Perez noted that the Philippine Senate has already approved the *Philippine Space Act,* signed into law August 13, 2019, paving the way for the formation of the Philippines Space Agency.

Noordin Ahmad [Malaysian National Space Agency—*Former Director General*] reported that in February 2019 the Malaysian Cabinet approved the merger of two agencies: the National Space Agency and the Malaysian Remote Sensing Agency. Several remote sensing projects are ongoing at the agency, e.g., forest mapping and monitoring, disaster management, and urban infrastructure mapping and monitoring.

The remainder of the first day included four presentations each on Agricultural LUCC and Land–Atmosphere Interactions and Emissions. Then on the second day, there were full-day parallel sessions on both these topics.

DAY TWO

Having introduced these two topics in the final presentations on the first day, the second day was dedicated to full-day parallel sessions on Agricultural LUCC and Land-Atmosphere Interactions and Emissions.

Agricultural LUCC

The agriculture session included the following parallel sessions: Agricultural LUCC and Geoinformatics; Rice Mapping and Monitoring in Asia; Modeling and Decision Support Systems; and a Panel Discussion on Agricultural Research Needs and Priorities. The highlights of the discussion are summarized here.

The GEOGLAM initiative was developed by GEO, which is a partnership of governments and international organizations, hosted at the World Meteorological Organization (WMO) in Geneva. The role of

The Local Media Learn the Importance of Land Use/Cover Change Science

A press conference was organized involving local reporters and meeting organizers from the UTM, NASA, NIES, and the University of Illinois Urbana–Champaign—see **Photo**, below. The organizers explained the significance of the meeting and why addressing LUCC is important in S/SEA countries considering rapid deforestation, conversion of agriculture to urban areas, and increased pollution due to biomass burning and motor vehicles in the region. Also, the organizers emphasized the importance of satellite remote sensing and Earth observations in addressing environmental problems in developing countries and the need to educate regional researchers through sharing data and training on how to use them.

A press conference held during the first day of the SARI LCLUC meeting provided an opportunity for meeting organizers to promote the importance of LUCC science to the local media in Malaysia. Pictured here are [*left to right*]: **Toshimasa Ohara** [NIES], **Kasturi Kanniah, Mohd Hamdan Ahmad** [University of Technologi Malaysia (UTM)—*Dean, Faculty of Built Environment*], **Wahid Omar** [UTM—*Vice Chancellor*], **Garik Gutman**, **Krishna Vadrevu**, **Chris Justice**, **Tsuneo Matsunaga**, and **Atul Jain** [University of Illinois Urbana-Champaign]. **Photo Credit**: UTM team

GEOGLAM is to coordinate satellite monitoring observation systems in different regions of the world to enhance crop production projections and weather forecasting data. Within this framework, starting in 2013 GEOGLAM developed the Crop Monitor reports of the Agricultural Market Information Systems (AMIS), which provide global consensus crop condition assessments. Given the success of the AMIS Crop Monitor, GEOGLAM developed the Early Warning Crop Monitor, which began in 2016 and focused on developing a consensus on crop conditions from international, regional, and national organizations for countries at risk of food insecurity.[5]

Monitoring Agricultural Changes for Profitability

In India, LUCC crop mapping using multitemporal data from the Advanced Wide Field Sensor on the Indian Remote Sensing Satellite is now complete. Sown areas for summer and winter crops and other LUCC information are provided on an annual basis. The data can be downloaded from *http://bhuvan.nrsc.gov.in/gis/thematic/index.php#*.

Agriculture accounts for 12% of the national gross domestic product (GDP) in Malaysia and employs 16% of the population. Palm oil, rubber, cocoa, and rice are the major crops. Malaysia currently accounts for 39% of the world's palm-oil production and 44% of the world's palm-oil exports. Large-scale palm-oil monitoring (e.g., using Landsat) is well established and successful; however, the main challenge is to identify individual disease/infection levels for oil palms. In contrast, rubber mapping in Malaysia is not done—because it is difficult to differentiate rubber from other green trees including young and mature rubber trees.

In Dong Thap and An Giang provinces of Vietnam, very high-resolution Planetscope data from 2010 to 2019 showed that rice paddies are being converted to other vegetation types (e.g., bamboo, melons, corn) as they are more profitable. Similar changes to those described for Malaysia were observed in the Red River Delta of Vietnam, where crop diversification is ongoing. In the Mekong Region, preliminary results suggest that existing dams do not have a major impact on river-flow dynamics, however, the impact of flow in tributaries could be significant depending on dam location.

Monitoring Agricultural Changes from Natural Phenomena

In the Philippines, El Niño-induced droughts had a significant impact on the reduction of corn production during 1997–1998, 2009–2010, and 2015–2016. Drought indices such as the Standardized Precipitation Index (SPI)[6] from the Tropical Rainfall Measuring Mission (TRMM) and other indices from MODIS[7] (e.g., Standardized Vegetation Temperature Ratio, Vegetation Health Index) and SPI-3 were congruent in terms of drought progression; however, these indices were weakly correlated with satellite retrieved soil moisture data from the Soil Moisture Active Passive (SMAP) satellite. Thus, a combination of satellite and ground-based measurements was recommended to address droughts. In the Indian states of Punjab and Haryana, wheat yield forecasting was done by combining MODIS vegetation indices using TIMESAT software,[8] which provided phenological parameters for 2009–2010 with reasonable prediction strength. Also, a crop-simulation model titled InfoCrop, a user-friendly crop modeling system, was used for crop-yield simulation for subsequent years, with very low error in Punjab and Haryana.

Radar-Based Studies for Crop Management

Some presentations in this session stressed the need to use synthetic aperture radar (SAR) data to map and monitor crops—due to persistent cloud cover in S/SEA that prevents other data acquisition techniques from being utilized. At the Philippines' International Rice Research Institute (IRRI), multitemporal Sentinel-1 SAR data are being used to routinely map rice in S/SEA countries and also to create in-season and end-of-season rice-yield forecasts. Also, SAR data have been used to map droughts in Thailand, India, and Cambodia. Sentinel-1 data were used to map inundation from Cyclone Titli, which occurred in October 2018, in Andhra Pradesh, India—damaging 26% of the estimated rice paddy. Meanwhile, in Malaysia, geospatial technology is being used for agricultural land-use mapping, soil surveys, precision farming, and yield forecasting. Specifically, RADARSAT data are being used to monitor crop management including land preparation, irrigation, planting, and harvesting. Sentinel-1 is effective for mapping rice paddy in cloud-prone tropical areas in monsoon Asia with double or multiple cropping systems. Other presentations showed results from Indonesia, which are similar to those obtained in Malaysia. Before 2013, only MODIS and Landsat data were used to track rice paddy dynamics, however, the Support Vector Machine approach—with an overall accuracy of greater than 95%—has been used to map paddy fields for 2018.

[5] To learn more about this topic, see "Increasing Information Access for Food Security Monitoring: Overview of the GEOGLAM Crop Monitor for Early Warning (CM4EW)" in the May–June 2019 issue of *The Earth Observer* [**Volume 31**, **Issue 3**, pp. 4–14—*https://go.nasa.gov/2U661yF*].

[6] SPI stands for Standardized Precipitation Index, and is produced by the Copernicus European Drought Observatory (EDO). The "SPI-3" is computed for a three-month accumulation period.

[7] MODIS stands for Moderate Resolution Imaging Spectroradiometer, which flies on NASA's Terra and Aqua platforms.

[8] TIMESAT is a software package for analyzing time series of satellite data (*http://web.nateko.lu.se/timesat/timesat.asp*).

Panel Discussion Summary

Chris Justice [*GEOGLAM Co-Chair and NASA Harvest Chief Scientist*] led a panel discussion with GEOGLAM researchers from each country identifying national priorities and "gaps" in agricultural monitoring. National priorities included the need for increased use of remote sensing in national crop-monitoring systems; support in moving research into the operational domain and the adoption of satellite-based monitoring and crop forecasting by operational agencies; developing incentives for *in situ* data sharing; and standardizing drought-monitoring. The gaps identified included the need to: build geospatial capacity in government and local agencies; expedite adoption of new technology by farmers and extension services; improve field-level monitoring for rapid and robust crop insurance claim settlements; establish remote sensing to monitor policy compliance and adoption by farmers; and standardize satellite methods and products. Reiterated throughout the discussions was the need for focused, regional workshops to share technical expertise and methods to monitor crops between countries as well as standardizing methods, products, and best practices. One reason there is such need to standardize methods within the community is that there has been a rapid proliferation of different techniques for rice mapping and monitoring in recent years, and the products resulting from each are not easily compared.

Land–Atmosphere Interactions and Emissions

The atmospheric parallel session included discussion of emission inventories and modeling of pollutants and biomass burning, including aerosols. There was also a panel discussion on atmospheric research needs and priorities. Thematic summaries are provided here.

Satellite Sources of Relevant Data

Presentations during this session included details on several satellites useful for emissions and fire monitoring. The GOSAT-1 and GOSAT-2 missions, launched in 2009 and 2018 respectively, have been providing columnar measurements of carbon dioxide (CO_2), methane (CH_4), and water vapor (H_2O), useful for climate change studies. In addition, GOSAT-2 provides chlorophyll fluorescence and a proxy-methane product. The GOSAT-2 products will be released through the NIES website.

The Visible Infrared Imaging Radiometer Suite (VIIRS) launched on the Suomi National Polar-orbiting Platform (NPP) [2011] and National Oceanic and Atmospheric Administration-20 (NOAA-20)[9] [2017] satellites, has 22 bands with global coverage every 12 hours. Data from the VIIRS M-band [750-m (2460-ft) resolution] and I-band [375-m (1230-ft) resolution] are useful for monitoring fires; M-bands 7–11 are particularly good for detecting combustion sources. VIIRS also has a low-light, nighttime imaging capability: the VIIRS Day-Night Band detects electric lighting, fires, and flares—down to the level of street lamps. The VIIRS nighttime products are available from *https://go.nasa.gov/2wKMVFr*.[10]

The Geostationary Operational Environmental Satellite–R (GOES-R) series, which currently includes GOES-16 [a.k.a., GOES-East, launched November 2016] and GOES-17 [a.k.a., GOES-West, launched March 2018],[11] carry the Advanced Baseline Imager (ABI) with 16 spectral bands and full-disk capture every 10 minutes, which provide additional fire detection and characterization capability using Band 7 [3.9 μm] data.

Specific to atmospheric correction, an algorithm titled Land Surface Reflectance Code (LaSRC), for correcting sensor measurements made at all resolutions: i.e., from coarse- to high-resolution for atmospheric effects, is available freely from **Eric Vermote** [GSFC] *ateric.f.vermote@nasa.gov*.

Greenhouse Gas Emissions and Other Pollutants from Human Activity

Other presentations focused on greenhouse gas (GHG) emissions. The historical emissions inventory for 1960–2015 for S/SEA, titled Regional Emission inventory in ASia (REAS), has been updated from Version 2.1 to Version 3.0. The monthly emissions inventory data cover sulfur dioxide (SO_2), oxides of nitrogen (NO_x), carbon monoxide (CO), nonmethane volatile organic compounds (NMVOC), particulate matter (both $PM_{2.5}$ and PM_{10}), black carbon (BC), organic carbon (OC), ammonia (NH_3), and CO_2. Emissions of all air pollutants in Asia increased significantly between 1950 and 2015; in particular, the largest contributor to emissions of NO_x in SEA is Indonesia, followed by Thailand, Philippines, Vietnam, and Malaysia.

Specific to the GHG emissions from food production, CH_4 is the most important greenhouse gas emitted from the rice paddies in S/SEA, with India and Indonesia being the highest emitters. Results from one of the Stability of Altered Forest Ecosystems (SAFE) site in

[9] NOAA-20 was formerly known as Joint Polar Satellite System–1 (JPSS-1). Three more JPSS missions are planned over the coming decade.

[10] To learn much more about applications for VIIRS DNB observations and other observations of our home planet after the Sun goes down, see *The Earth at Night*, which can be downloaded as an eBook or PDF from *https://www.nasa.gov/connect/ebooks/earthatnight_detail.html*.

[11] Two more GOES-R satellites (GOES-T and -U) are planned for launch in 2021 and 2024, respectively.

Sabah [Borneo, Indonesia] suggests that riparian strips are efficient in CH_4 uptake, however, they can also be a source for nitrous oxide (N_2O) and CO_2 emissions.

In the Philippines for 2013 there was one motor vehicle for every 12 people. Motor vehicle exhaust produces tiny airborne particulate matter and other pollutants that are hazardous to health; thus, addressing air pollution from mobile sources is one of the major concerns in the Philippines. In Southern Thailand, both motor vehicle emissions and biomass burning dominate over other sources. Ambient particles smaller than 100 nm ($PM_{0.1}$) dominate the aerosol particles. In East Asia (EA), 11 countries participate in a nanoparticle monitoring network titled EA-nanonet, which provides monthly measurements.

Atmospheric Effects from Natural and Human-Caused Fires

Vegetation fires in S/SEA are a recurrent problem. Trends in vegetation fires using data from MODIS [2003–2016] and VIIRS [2012–2016] suggest increasing numbers of fires in India, Cambodia, and Vietnam. In South Asia, agricultural fires dominate in India, Pakistan, and Sri Lanka, whereas the fires are mostly natural (i.e., forest-related) in Nepal and Bhutan. In SEA, Thailand, Timor Leste, and the Philippines, agricultural fires are the dominant source; conversely, in Malaysia, Cambodia, Brunei, and Myanmar, forest fires are dominant. Also, fires show a strong negative correlation with precipitation, which acts as a fire suppressor. In Indonesia, the provinces of Riau and Jambi are hotspots of peatland biomass burning—where aerosol optical depths above 5.0 have been observed. In the peatlands, the depth of the water table determines the amount of peat that can burn, i.e., most of the fires occur on surfaces where the ground water level (GWL) is below 20 cm (7.9 in). In degraded peatlands, GWL has less influence. In Chiang Mai, Thailand, BC and brown carbon (BrC) emissions from fires can affect planetary boundary layer (PBL) development the next day, producing high and persistent air pollution. To address the PBL dynamics, ground-based measurements such as lidar are quite useful.

In Malaysia, 65 continuous automatic air quality monitoring stations from the Department of Environment measure $PM_{2.5}$, PM_{10}, and other gases such as SO_2, NO_X, CO, CH_4, ozone (O_3), and non-methane hydrocarbons (NMHCs). In addition, they measure meteorological parameters from industrial, residential, traffic, and rural areas. Further, 14 stations from the meteorological department measure total suspended particles and nine stations measure PM_{10}. Additionally, three AErosol RObotic NETwork (AERONET) stations measure aerosols (*http://aeronet.gsfc.nasa.gov*). There is a strong need to address aerosol impacts on radiative forcing and to address particulate matter pollution impacts on health in Malaysia.

An air pollution mitigation study using the Asian-Pacific Integrated Model (AIM) model suggested several measures to curb pollution in S/SEA, e.g., use of end-of-pipe mitigation measures (achieved through improving fuel quality, such as by shifting to fuels with lower sulfur content); improving energy efficiency through high-energy efficient technologies; and through drastic energy shift, e.g., from coal to renewables or natural gas.

Panel Discussion Summary

Tsuneo Matsunaga led the atmospheric research needs and priorities panel discussion. The panel included representatives from Malaysia, Vietnam, Indonesia, Philippines, Thailand, Japan, China, and Singapore. All researchers highlighted the need for more atmospheric research projects in S/SEA. The various panelists identified potential solutions to reduce air pollution in the region, which included targeting the energy sector to reduce emissions, biomass burning, transportation, and adopting low carbon strategies, e.g., introducing more public transportation options. Participants also identified the need to develop integrated emission inventories to mitigate pollution, including more funding for monitoring stations. On translating the research to operations, panel members felt the need to develop integrated assessment systems to map and monitor pollution regularly in different countries. Citizen science and linking pollution to human health were also suggested as important topics of priority. All participants highlighted the need for more training activities in the region.

DAY THREE

The third day included sessions on forest and urban LUCC. The meeting ended with a plenary discussion, which included a regional science summary and overview of research and capacity-building priorities in SARI countries. The fifteen presentations that were delivered on the final day of the meeting showcased the latest remote sensing approaches for forest and urban mapping and monitoring in the region.

Forest LUCC

In SEA, Myanmar, Laos, and Cambodia approximately 44,000 km^2 (17,000 mi^2) of rubber has been planted between 2003 and 2014. Of that amount, 50% has been planted on former evergreen forest lands, 18% on deciduous forest land, and 32% on low-vegetation areas; a significant amount of rubber plantation expansion took place in that time period. In these countries, rubber expansion is mainly attributed to governmental policies that promoted foreign investments in the industrial plantations as a win–win solution to alleviate poverty in remote rural areas. However, the recent 2019 and 2020 forecast for rubber prices suggests a significant decline, which could reduce rubber expansion and lead to replacement in the future.

In Malaysia during 2018, the Forest Research Institute (FRI) experimented with using both airborne lidar and drones equipped with red–green–blue (RGB) cameras to estimate forest above-ground biomass (AGB) and for forest mapping in some project areas. The results seem promising and the FRI plans to extend the approach to larger regions. Analysis of data obtained between 2007 and 2017 from the Phased Array type L-band Synthetic Aperture Radar (PALSAR), which flies on the Japanese Advanced Land Observing Satellite (ALOS), suggests a decline in overall forest cover. The first above-ground forest biomass map for peninsular Malaysia was developed in 2017 using ALOS PALSAR data. In Andhra Pradesh, India, some smallholder farmers are transitioning from agriculture to plantations. The probability that a farmer or household will adopt forest plantation increases with increased distance to the market and income decreases with the increase in the area of land owned. Using a combination of the Harmonized Landsat–Sentinel-2 (HLS) 10-m (33-ft) surface reflectance data and PlanetScope 3-m (10-ft) data,[12] forests can be separated from other land covers, and plantation forests from natural forests. However, plantation types (e.g., palm vs. banana) are more difficult to discriminate using standard machine learning techniques. For wetland monitoring, integration of Landsat 8, Sentinel-2, and Sentinel-1 data can provide useful information on water-regime mapping.

Forest biomass quantities are poorly documented in different regions of the world—in particular, the tropics. Biomass measurements at higher resolution and with defined error tolerance are needed to address the LUCC-related carbon fluxes. Also, repeated mapping and monitoring of forests is needed to identify deforestation and growth. ESA's Biomass mission[13] will provide such observations. In Malaysia, AGB was derived from airborne lidar at the Ayer Hitam Forest Reserve, which is dominated by dipterocarp forest. The results indicate a high positive correlation between lidar-derived tree height and field-measured tree height. In addition, AGB estimation using airborne and terrestrial lidar in lowland forests showed high correlation.

[12] The PlanetScope constellation is a fleet of 120 satellites, collecting daily 3-5-m (10-16-ft) resolution imagery of Earth's entire landmass.

[13] Biomass is the seventh Earth Explorer mission planned for launch in the 2022 timeframe (*https://go.nasa.gov/33u015L*).

Urban LUCC

In Malaysia, the national government supports the development of *smart cities*, which are defined as cities that are free from physical, social, and mental threats, where the community is able to live in peace and harmony and in a well-protected and conducive living environment. Eight smart-living elements have been identified that include safety and security of people, low-carbon lifestyle, improving housing quality, educational quality, health conditions, cultural facilities, and tourist/recreational attractiveness. In addition, Malaysia's Safe City Programme is being implemented in 150 municipalities to reduce crime. The Programme includes: a street lighting program in different locations; developing a Safe City monitoring web application system wherein people can report crime or unsafe activities directly to police and local authorities online; and crime prevention through environmental design, i.e., designing and managing the built environment to ensure safety in cities. Other presentations in this session stressed the need for more green cover in cities and emphasized that the spatial arrangements and proportions of different land-cover features such as residential, industrial, commercial, and green cover can affect local heating and cooling in urban environments.

Concluding Plenary Discussion

Chris Justice and **Krishna Vadrevu** co-led the final discussion session, which involved all participants, and focused on the SARI regional research needs and priorities. During the discussion, the regional researchers emphasized the need to continue these meetings and training events for the benefit of the larger LUCC community. All agreed that free and open data policies from all regional agencies are needed to strengthen the LUCC research. In addition, attention should be given to transitioning basic research to develop operational satellite-based products. There was also an emphasis on developing guidelines to determine best practices specific to accuracy assessment protocols for LUCC data products. Also, all participants stressed the need for increased capacity building and training activities in the region through SARI activities.

After the discussion session, **Garik Gutman** expressed thanks to all sponsors, participants, and organizers of the meeting, and then adjourned the meeting

After-Meeting Training Sessions

A three-day, hands-on training session was held immediately after the meeting, with participation by 85 young researchers. The focus was on the use of remote sensing and geographic information systems for LUCC applications. The training was organized as a part of the Committee on Earth Observations (CEOS) Working Group on Capacity Building and

Figure. Shown here are photos taken during the three-day SARI LCLUC and CEOS WGCapD training event that followed the SARI LCLUC meeting. These include: the training registration team (UTM) [*top left*]; **Thuy Le Toan** [Centre d'Etudes Spatiales de la Biosphère (CESBIO), France] delivering a training lecture [*top right*]; **Kasturi Kanniah** [UTM, *standing on the right in the bottom left photo*] awarding training a certificate of completion to one of the participants [*bottom left*]; and three different attendees showing their training certificates [*bottom right*]. **Photo credit**: UTM Team

Data Democracy Training [WGCapD], SARI and GOFC-GOLD S/SEA regional network activities. Six international trainers covered a variety of LUCC topics including forest cover mapping and monitoring, forest disturbance mapping, fire detection and monitoring, crop area mapping, and carbon cycle modeling. All training sessions focused on hands-on activities. At the conclusion of the training session, **Kasturi Kanniah** (UTM) awarded certificates of completion to all participants. The photos in the **Figure** [*above*] capture some highlights from the event.

Conclusion

SARI, the NASA LCLUC research initiative, is strengthening land-change science by involving regional scientists. In particular, this meeting highlighted the needs and priorities for SARI and the LCLUC program, which includes an increased emphasis on local LCLUC research and case studies, drivers and impacts of LCLUC, the science of forecasting, interdisciplinary research, and relevance to decision making. The press conference held during the meeting was a great outreach opportunity for meeting participants to connect with the local media and inform them about issues relating to LUCC in Malaysia. The training event, held immediately after the meeting, also went well. It helped to showcase the latest methodologies and NASA LCLUC products. It also engaged several early career researchers in the region to learn about remote sensing and geospatial technologies.

In addition to this summary report, several other meeting outputs either have been or will be produced.[14] The next SARI meeting and training event is planned for late 2020. ■

[14] Three journals plan to publish Special Issues related to topics covered at the SARI LCLUC meeting. They include *Forests*, (*https://go.nasa.gov/2JbvUa1*); *Land Degradation and Development*, (*https://go.nasa.gov/3a1tEhi*); and *Remote Sensing*, (*https://go.nasa.gov/392Ip1Z*).

Summary of the 2019 GRACE and GRACE Follow-On Science Team Meeting

Felix Landerer, NASA/Jet Propulsion Laboratory, felix.landerer@jpl.nasa.gov
Carmen Boening, NASA/Jet Propulsion Laboratory, carmen.boening@jpl.nasa.gov

Introduction

The second joint Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) Science Team Meeting [GFO STM] took place October 8-10, 2019. NASA/Jet Propulsion Laboratory (JPL) hosted the meeting at the California Institute of Technology campus in Pasadena, CA. The 2019 GFO-STM marked the first STM after the public release of the new GRACE-FO science data that began in April 2019. More than 110 participants—see photo below—attended the meeting, which consisted of 66 oral and 21 poster presentations distributed across topical sessions. After an update on the status of GRACE-FO, the remainder of this article presents a summary of the meeting. The complete GFO STM program, abstracts, and many of the presentations will be available at *https://grace.jpl.nasa.gov*.

Update on GRACE-FO

The GRACE-FO continuity mission, launched on May 22, 2018, has been providing monthly gravity and mass change observations since June 2018. As of April 2020, the GRACE-FO project team has processed and released 19 monthly gravity fields—the most recent from February 2020. The primary mission objective of GRACE-FO is to provide continuity from the monthly mass-change observations of GRACE via its Microwave Interferometer (MWI). (GRACE ended science operations in June 2017, resulting in a data gap of a little over a year between GRACE and GRACE-FO; the team is working to bridge that gap, as discussed in this summary.) The continuity mission also operates a novel Laser-Ranging Interferometer (LRI) as a technology demonstration and as an enabling technology for future GRACE-like missions and more-accurate, satellite-to-satellite ranging observations.

The twin GRACE-FO satellites are tracking Earth's water movement and global surface mass changes that arise from climatic, tectonic, and anthropogenic forces and enable new insights into ice sheets and glaciers, land water storage, and changes in sea level and ocean currents—with important applications for everyday life. GRACE-FO is a U.S.-German collaboration between NASA and the GeoForschungsZentrum (GFZ) [German Research Centre for Geosciences]. The in-orbit checkout phase for GRACE-FO ended in January 2019, wrapping up the initialization, calibration, and performance assessment of the MWI system, the accelerometers, and the experimental LRI by the project's Science Data System (SDS) team. The mission is now in its science operations phase, which will last until 2023—five years since launch.

DAY ONE

The first day of the meeting focused on providing the science team members with a detailed assessment of the status of the GRACE-FO mission, and the instrument and science performance assessment from the mission's SDS team. There were also reports on plans to reprocess GRACE data, and plans to bridge the data gap between GRACE and GRACE-FO, and to evaluate intermission continuity.

GRACE-FO and GRACE Project Status

After host **Michael Watkins** [JPL—*GRACE-FO Science Lead*] welcomed the participants, **Felix Landerer** [JPL—*GRACE-FO Project Scientist*] began with an overview of the GRACE-FO satellites and their instrument status, summarizing the performance of the main science instruments: the MWI [including global positioning systems (GPS)], accelerometers, and star cameras. Landerer highlighted that GRACE-FO is meeting its goal of extending the GRACE record at an equivalent precision and spatiotemporal sampling. During its first 20 months in orbit, GRACE-FO observed large interannual terrestrial water and ice mass variations associated with excess rainfall (in the Central U.S. and Middle East), drought

Photo 1. 2019 GRACE and GRACE Follow-On Science Team Meeting participants. **Photo credit**: Sylvia Ascencio [JPL]

(in Europe and Australia), and ice melt (in Greenland). The observed mass changes are consistent with independent mass change estimates derived from precipitation and temperature data. This consistency, the overall GRACE-FO measurement system performance, and the geophysical signal assessments provide high confidence that no biases exist between the two missions, despite the gap.

A series of status reports on programmatic mission operations, science operations, and science data system processing followed, during which:

- **Mona Witkowski** [JPL] reported on the ground and mission operations at the German Space Operations Center (GSOC), which is responsible for GRACE-FO spacecraft operations;
- **Himanshu Save** [University of Texas, Center for Space Research (CSR)] provided an overview and assessment of the science operations;
- **Tamara Bandikova** [JPL] reviewed the status of GRACE/GRACE-FO Level-1 (L1) reprocessing at JPL;
- **Christopher McCullough** [JPL] provided an overview of the newly developed accelerometer calibrations for GRACE-FO; and
- **Bruno Christoph** [Office National d'Études et de Recherches Aerospatiales (ONERA), the French Aerospace Laboratory] presented a performance assessment of the GRACE-FO accelerometer instruments.

After these status reports came a block of presentations related to the status of the experimental LRI. **Sam Francis**, **Willy Bertiger**, **Hui-Ying Wen**, **Sujata Goswami** [all from JPL] each focused on processing details and early results of the highly precise laser-ranging measurements (which provide as much as 30 times more-accurate satellite-to-satellite ranging than MWI).

The three mission SDS centers (JPL, GFZ, and CSR) summarized the status of the latest Release-06 (RL06) Level-2 (L2) gravity field products, including an overview of background dealiasing models (GFZ), new JPL mascons (JPL), and new data-processing strategies [e.g., via range acceleration (CSR)]. The first gravity field results from the LRI measurement show results consistent with the primary microwave-ranging processing, and demonstrate some potential for advances by exploiting the very low noise level of the LRI measurement. This could lead to new science applications of rapid mass change such as earthquakes, tsunamis, and flood events.

Byron Tapley [CSR—*GRACE Principal Investigator*] gave the final presentation in this session, laying out the plans for the final release of GRACE data—Release-07 (RL07). He discussed the ongoing data-reprocessing efforts and the need to implement robust approaches to bridge the gap between GRACE and GRACE-FO to ensure the goal of a consistent long-term gravity and mass-change data record.

DAYS TWO AND THREE

The second and third days of the meeting featured six science sessions, with presentations that included: analytical techniques for gravity-mission data; methods to bridge the gap between the end of science operations for GRACE and beginning science data collection with GRACE-FO; science analysis of mass-transport data in the fields of hydrology, oceanography, glaciology, and solid-Earth sciences; and a discussion of GRACE and GRACE-FO applications in the broader context of NASA's Applied Science Program. The final meeting session focused on concepts and implementation studies for future gravity missions. In addition, posters relevant to each topic were on display for discussion throughout the meeting.

Continuity and Analysis Techniques

The Continuity and Analysis Techniques session continued the assessment by the science team of the first year of released GRACE-FO data in more detail, including the inter-mission continuity with GRACE.

In the ocean domain, results shown during this session revealed that ocean-bottom pressure can be reconstructed and estimated using atmospheric reanalysis data—thereby providing a proxy to assess the performance of GRACE-FO data. No biases were observed based on solution analysis and independent data over the ice sheets.

The assessment of the first GRACE-FO gravity fields by the science team members showed overall good agreement with extrapolated GRACE estimates. Small differences in the gravity-field data-processing parameters between GRACE and GRACE-FO point to the need for further analysis to understand how these differences trace back to the instrument and measurement system. However, an assessment of gravity-field errors across the official SDS solutions highlighted the overall good performance of GRACE-FO data.

Several groups have already started to analyze the new LRI data and compare it to the conventional microwave ranging observations. Overall, the noise level for the LRI is lower than that for the MWI, opening up the possibility of using the LRI data for applications that require more higher-accuracy observations than the MWI can provide, e.g., observing earthquakes, tsunamis, or floods as the two GRACE-FO satellites pass directly overhead.

Of great importance for accurate mass-change estimates are robust observations of low-degree (large-scale) gravity coefficients. Updated geocenter results use Global Navigation Satellite System (GNSS) observations of orbit tracking, point positioning, and GRACE/GRACE-FO in a unified inversion. Satellite Laser Ranging (SLR) observations, discussed by groups from NASA's Goddard Space Flight Center (GSFC) and CSR, remain a vital contribution to augment GRACE-FO observations with accurate large-scale gravity observations. Finally, new approaches that combine satellite gravity observations with solid-Earth deformation measurements from ground-based GPS networks are enabling improvements in the spatial resolution of mass-change estimates, and also provide a way to bridge the gap between GRACE and GRACE-FO.

Mean Gravity Field and Cryosphere

This session started with a summary of the final reprocessing of Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)[1] gravity-field data, which yielded significant improvement in the estimated static gravity field. The next presentation discussed the particular challenges of measuring geoid changes in the presence of compact mass changes, such as in Alaska's glacier region. Augmenting GRACE data with airborne altimetry observations allows a much higher-resolution geoid characterization in Alaska than was previously possible.

Another presentation focused on assessing the continuity of GRACE-FO measurements of ice-mass losses in Greenland (see **Figure**), in Antarctica, in small glaciers and ice caps, and in the scattered glaciers of High-Mountain Asia—all from 2002 to 2019. GRACE/GRACE-FO—for the first time—provides worldwide,

[1] GOCE was the first of the European Space Agency's Earth Explorer missions to launch; it launched in 2009 and ended in 2013. The mission provided high-resolution observations of Earth's persistent static gravity field.

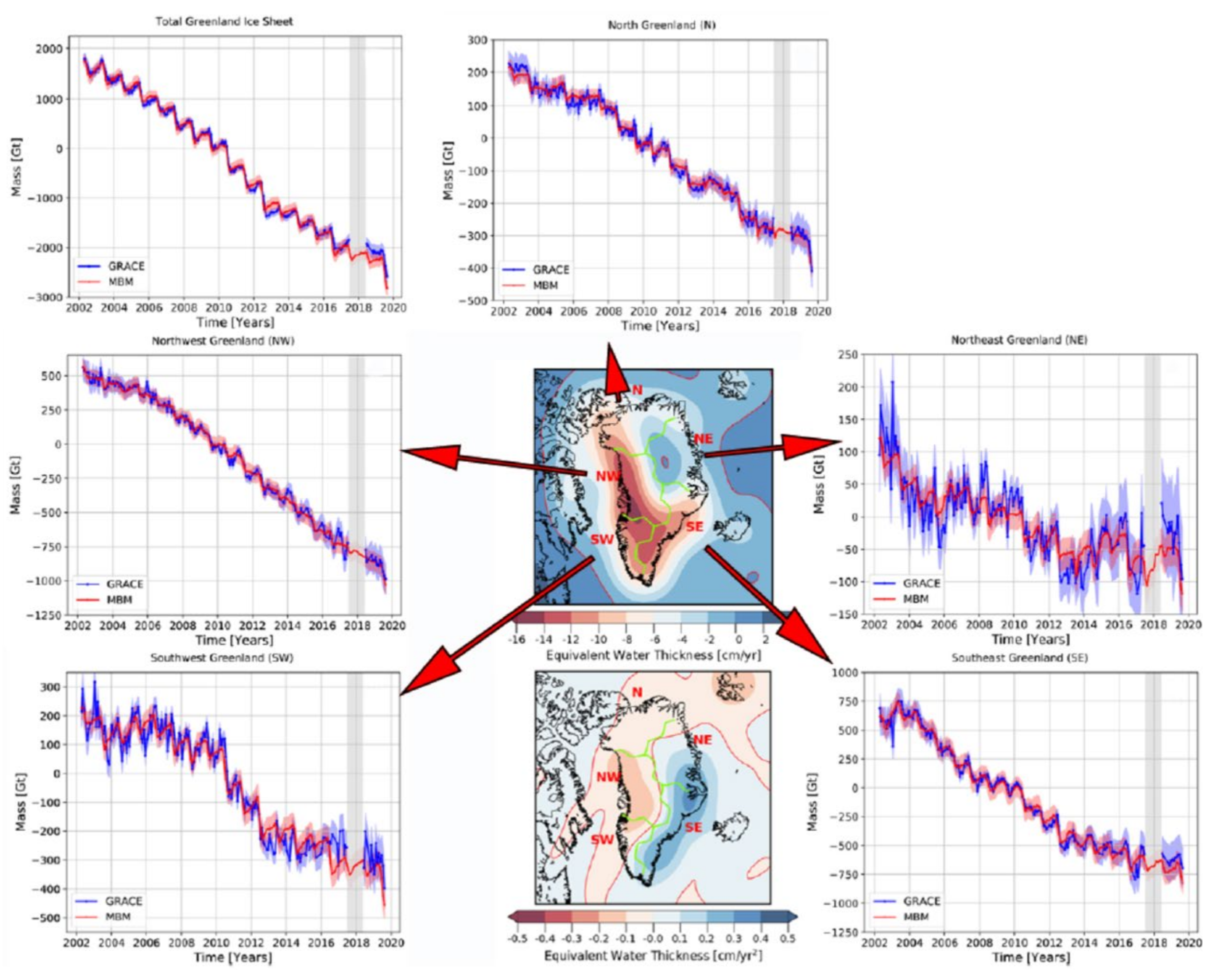

Figure. The center map shows the average mass loss in centimeters per year from 2002 to 2019, while the bottom center map shows acceleration in mass loss in cm²/year. The graphs show mass change data from GRACE and GRACE-FO for parts of Greenland (as identified on the center map) using the JPL fields (*blue*) versus the adjusted Mass Budget Method (MBM) (*red*). MBM calculates the ice sheet mass change as the net input of mass at the surface (essentially snowfall minus runoff, evaporation, sublimation, and wind transport) versus net output of mass at the periphery (the ice flux across the junction with the ocean). Results are shown for the Greenland Ice Sheet [*top left*], and the individual regions in gigatons, where 1 Gt = 10^9 and t = 10^{12} kg. **Image credit:** American Geophysical Union continuous, precise, monthly observations of all ice sheets and glaciers. Comparing different solutions showed that the mass-loss estimates are reliable, accurate, and consistent through the data gap.

Solid Earth Science

This session covered a range of topics, including geodetic strategies for improving the terrestrial reference frame, viscoelastic behavior of subduction-zone earthquakes, improved estimates of glacial isostatic adjustment (GIA), and hydrotectonic loading observations and their joint analysis with satellite gravimetry. A critical assessment of recent results on the 2011 Tohoku–Oki magnitude (M_w) 9.0 earthquake east of Japan's Honshu Island indicated that previously hypothesized precursory gravity changes seen in GRACE data are likely not statistically significant, and thus may not be related to the earthquake but rather a random variation in the data. Meanwhile, earthquake-correction models that account for coseismic as well as postseismic signals are being developed for eleven M_w 8.0 and larger earthquakes that occurred between 2002 and 2017 to separate the immediate and long-term (i.e., years-to-decades) signatures of earthquakes in the satellite gravity record. In most cases, the cumulative long-term, postseismic signal has already exceeded the coseismic gravity amplitude, highlighting the importance of these phenomena. Another presentation on GIA for Antarctica highlighted the rapid viscoelastic land motion over West Antarctica, indicating that these kinds of effects will have to be taken into account when assessing the ice sheet's ongoing ice-mass changes as the satellite gravimetry record lengthens.

Hydrology

This session focused on recent advances in understanding large- and small-scale changes related to land water storage and its components (e.g., groundwater, soil moisture, snow), as well as using satellite gravimetry observations to improve forecasts for drought, freshwater availability, and vegetation conditions, and to assess ecosystem vitality. Several presentations discussed recent progress on the data combination and joint analyses of vertical land motion [from GPS, interferometric synthetic aperture radar (InSAR), altimetry] and satellite gravimetry. In the U.S. Great Lakes region, strong solid Earth deflections—as much as 4 mm (0.16 in) per year—from increased lake storage must be accounted for when using GPS station deformation data to constrain GIA models.

Other presentations in this session reported on progress in understanding the dynamics of seasonal groundwater changes in California by using data from groundwater wells and GRACE. GRACE and GRACE-FO data provide consistent estimates of ongoing glacier changes in the High Mountain Asia region. Such satellite gravimetric observations provide a unique, direct constraint on the precipitation amounts at the regional scale, which allows the diagnosis of simulated glacier and snow changes and recharge, thereby directly informing water security in the Himalaya region. Precipitation estimates over cold regions in particular are prone to biases due to sensor and network shortcomings, but GRACE and GRACE-FO observations provide crucial observational capabilities to estimate net large-scale snowfall. Overall, the session highlighted that combining satellite gravimetry with dense GPS vertical deformation observations will enable higher-resolution mass-change data going forward. Further, as data from new sensors become available [e.g., from the NASA–Indian Space Research Organisation (ISRO) Synthetic Aperture Radar (NISAR) mission, scheduled to launch in 2022], spatial and temporal downscaling of GRACE and GRACE-FO land-water storage products will become increasingly more feasible, particularly in data-assimilation frameworks.

Oceanography

As in the other sessions, several ocean-focused analyses assessed the first GRACE-FO data to bridge the gap with GRACE data. Global ocean mass change measured with GRACE-FO was confirmed to be unbiased relative to measurements from GRACE, allowing the continued assessment of the global sea-level budget in combination with distributed buoy networks (e.g., the array of Argo profiling floats that provide profiles of temperature and salinity—*http://www.argo.ucsd.edu/About_Argo.html*) and sea-surface-height observations from altimetry satellites. Recent biases in Argo salinity readings—and possibly in the satellite altimetry record—underscored the importance of the satellite gravimetry record to measure global mean sea level and its implications for net ocean heat uptake (over 90% of the net Earth heat gain ends up in the ocean). The data record from GRACE and GRACE-FO is also essential to calibrate glacier and ice sheet surface-mass balance models, which in turn has allowed reconstruction of those mass changes over the last 40 years. Knowledge of the spatial mass-loss patterns is essential to calculate the *sea-level fingerprint*, which describes the spatial distribution of associated sea-level changes. A preliminary analysis of the deep-water formation in the Southern Ocean showed that GRACE can recover the transport variability of Weddell Sea Bottom Water, given knowledge of the bottom pressure gradients and of winds over the Southern Ocean. Another presenter discussed how GRACE data can be used to extract useful information on submonthly bottom pressure variability and associated currents. This points the way toward future assimilation of such signals in ocean models, e.g., Estimating the Circulation & Climate of the Ocean (ECCO; *http://www.ecco-group.org/products.htm*), with the potential to improve circulation estimates and predictions.

Applications

John T. Reager [JPL—*GRACE-FO Deputy Program Applications (DPA) Lead*] summarized the GRACE-FO Mission Applications activities over the last four years. He discussed the GRACE Mission Applications Plan and workshops and tutorials that have been held. Reager also presented the results of a survey in the context of NASA's ongoing *Mass Change Designated Observable Study* (discussed in greater detail under "Future Concepts" on page 31), which supports mission formulation and requirement definitions in response to the recommendation of the 2017 Earth Science Decadal Survey (ESDS).[2] High-spatial-resolution and low-latency data products are critical for applications, as is *disaggregation* (i.e., separating terrestrial water storage into groundwater, soil moisture, surface waters, and snow and ice). The needs of most operational applications are challenging for space-based gravimetric sensors to meet. For example they typically require at least 25-km (15.5-mi) spatial resolution, weekly sampling, and low latency (i.e., rapid data product delivery in a few days after data aquisition.) These standards push the limits of existing gravimetric sensors, but progress has been made using data assimilation and data combination frameworks.

Future Concepts

The last session highlighted future technology developments (i.e., hybrid atomic-electrostatic accelerometers) and mission architecture studies (i.e., with small satellites and multisatellite constellations) for improved and more efficient measurements of mass transport. Progress was reported on improved metrics (known as *space-time accuracy grids*) for linking science objectives with particular mission architectures. Mass Change is one of the five Designated Observables identified in the 2017 ESDS. The Mass Change study team provided a comprehensive update on the development of the Science and Applications Traceability Matrix (SATM)[3] for Mass Change. The SATM reflects comprehensive input from the community to help the Mass Change team identify and characterize a diverse set of high-value, mass-change-observing architectures that are responsive to the Decadal Survey's scientific and application objectives for continuously measuring and understanding mass change.

Conclusion

The GFO STM highlighted the broad range of science analysis and applications that are supported and enabled by satellite gravimetry observations. The first GRACE-FO data—which have been available since June 2018—are of high quality and enable the continuity of the mass-change data record at a level of performance consistent with that of GRACE. The successful novel laser-ranging technology provides the potential for new science applications, and progress has been made in combining gravity data with data from other sensors to achieve improvements in resolving geophysical signals with improved spatial and temporal resolution. The multinational mission and science operations team—made up of members of the GSOC, GFZ, JPL, and CSR, together with industry support—is efficiently and successfully working to continue the long-term data record of gravity and mass change, laying the foundation for future discoveries of Earth's water cycle and mass transport processes. The next GFO STM will be held October 25-27, 2020, at GFZ in Potsdam, Germany. ■

[2] The 2017 ESDS, "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observations from Space," guides the plans for Earth science over the next decade. Among its recommendations, it establishes five Designated Observables (DO) to be implemented as cost-capped medium- to large-sized missions with NASA leadership. The full report can be downloaded from *https://go.nasa.gov/2JdDHUz*.

[3] The Science and Applications Traceability Matrix (SATM) provides the basis for much of the Mass Change team's deliberations and forms the foundation for their recommendations. The latest Mass Change SATM (and other documentation on the Mass Change Designated Observable) can be downloaded from *https://go.nasa.gov/2UEzAaJ*.

Summary of the 2019 NASA Atmospheric Sounding Community Activities

Eric Fetzer, NASA/Jet Propulsion Laboratory, eric.fetzer@jpl.nasa.gov

Introduction

As it does every year, the NASA atmospheric sounding community held two meetings in 2019, which highlighted the community's activities for the year. The first 2019 meeting was the Atmospheric Infrared Sounder (AIRS) Science Team Meeting (STM), held in Pasadena, CA, April 3-5, 2019, at the Beckman Institute at the California Institute of Technology. The second 2019 meeting was the NASA Sounder STM, held in College Park, MD, September 25-27, 2019, at the University of Maryland Conference Center. The Sounder Science Team is pictured below.

While the agendas of the two meetings have considerable overlap, participants at the AIRS STM primarily share results from the AIRS instrument, and Sounder STM participants tend to address topics that are more broadly relevant to the international constellation of past and present sounder instruments, as well as planned instruments.

Current operating satellite sounders include six hyperspectral infrared instruments, the most recent being the Infrared Atmospheric Sounding Interferometer (IASI), launched on the European Operational Meteorology (MetOp-C) satellite platform in November 2018. In addition to hyperspectral infrared instruments, a fleet of orbiting microwave instruments has provided a decades-long observational record. Also, many orbiting sounding instruments take collocated observations, either through formation flying (e.g., the Afternoon Constellation, or "A-Train")[1] or by virtue of shared spacecraft, and *in situ* observations are often obtained in locations where satellite instruments observe remotely. The satellite sounding instruments were described in detail in a previous Sounder Community Update in *The Earth Observer*[2] so that information is not repeated here. These collocated observations—along with model simulations—are increasingly important in interpreting sounder observations. This wide variety of datasets and the broad community of users extending beyond NASA, present many opportunities for interesting and important science. Some of those scientific results are shared here.

The remainder of this report summarizes the two meetings, highlighting a few of the presentations from each. The presentations that appear here were chosen because they reflect important new science results, significant technological advances, or give an overview of the state of the field. Some topics covered at one or both of these meetings—but not included in this summary—are: updates on sounder instrument calibration; a common microwave retrieval algorithm, and multiple infrared retrieval algorithms;[3] the analysis of collocated multisensor observations from the A-Train; comparisons between sounder observations; model reanalysis data; and observations from Global Positioning System (GPS) radio occultation instruments. Presentations from both meetings can be downloaded from the AIRS project website at *https://airs.jpl.nasa.gov/events*.

Spring 2019 AIRS Science Team Meeting

The AIRS STM began with an introductory session. **Joao Teixeira** [NASA/Jet Propulsion Laboratory (JPL)—*AIRS Science Team Leader*] gave opening remarks and discussed the status of the AIRS Science Team and the implications of an expected exit from the A-Train in coming years. **Gail Skofronick-Jackson** [NASA Headquarters (HQ)—*Program Officer for Atmospheric*

[1] A-Train is a nickname for the Afternoon Constellation, which includes Aqua, Aura, and several other NASA and international missions flying in formation. More details are available at *https://atrain.gsfc.nasa.gov*.

[2] See "Review of Atmospheric Sounding Instruments and Their Contributions to NASA Earth Science," which appears in the "Overview of 2017 NASA Sounder Science Community Activities" in the March–April 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 2**, pp. 12-13—*https://go.nasa.gov/3a2KQml*].

[3] For more on these topics, see: National Research Council (2004), *Climate Data Records from Environmental Satellites: Interim Report*, National Academies Press, Washington, DC.

Participants at the 2019 NASA Sounder STM in College Park, MD. **Photo credit:** Ruth Monnarez [JPL]

Dynamics] provided a NASA HQ perspective on atmospheric sounding, noting the significance of sounding science in the context of other Earth science disciplines. She also noted the importance of soundings in the Program of Record described in the 2017 Earth Science Decadal Survey.[4] **Tom Pagano** [JPL—*AIRS Project Manager*] described the status of the AIRS instrument and noted it remains in good health after nearly 17 years of operations. **Ruth Monarrez** [JPL—*Sounder SIPS Lead*] gave an update on the status of the Sounder Science Investigator-led Processing System (SIPS)[5] at JPL, and its continuing coordination with the AIRS project.

After the opening presentations, the remainder of the meeting agenda consisted of sessions on Weather and Climate, Atmospheric Composition, Applications, Retrievals and Validation, and Calibration and Level-1 Observed Radiances, and concluded with a Science Discussion.

As in earlier meetings, the agenda began with scientific interpretation of sounder datasets, with instrument-related issues discussed later in the meeting, and then a science wrap-up. Five presentations from the AIRS STM are highlighted in this report; the reader is referred to the URL in the Introduction for the agenda and a complete list of presentations.

Xianglei Wang presented the work of **Colten Peterson** [both at University of Michigan], showing results of an analysis of a spectrally resolved, outgoing, longwave-radiance dataset, constructed by combining data from AIRS and from the Clouds and the Earth's Radiant Energy System (CERES) instrument on NASA's Aqua platform, with model results. These data span the entire Aqua period (2002–present). Peterson diagnosed well-known changes to the radiative environment in the Arctic and concluded that many of the changes in the Arctic greenhouse effect are due to surface warming, but that different infrared spectral bands have different trends, and those are due to changes in atmospheric structure. The spectrally resolved radiation datasets used in the study are now available through the Goddard Earth Sciences Data and Information Services Center (GES DISC).[6]

Hartmut Aumann [JPL] examined the implications of small downward trends in reflected shortwave radiation as measured by the visible and near-infrared channels on AIRS. He showed that the AIRS trends are consistent with those in climate models, but that both AIRS and climate model trends show only half the downward trend of the CERES reflected shortwave measurements, although these differences are small when the trend uncertainty estimates are taken into account. He noted that all three datasets indicate slight decreases in reflected sunlight, consistent with a slight global reduction in reflective cloud amount.

Chris Barnet [Science and Technology Corporation] described an evaluation of the assimilation of shortwave infrared (SWIR) radiances into weather forecast models, using observations from the Crosstrack Infrared Sounder (CrIS) on the Suomi National Polar-orbiting Partnership (NPP) satellite. This study was motivated by a major advantage of future SWIR-only instruments over existing ones combining SWIR and longwave infrared (LWIR) (e.g., CrIS and AIRS): their much smaller cooling requirements can significantly reduce their mass and power—and associated costs—compared to sounders making LWIR measurements. Barnet noted that current data assimilation techniques do not take advantage of SWIR radiances and need to be reformulated to accommodate the more-complicated noise characteristics of SWIR over those of LWIR and their extra sensitivity to sunlight. He showed that while SWIR data have slightly lower overall information content than LWIR data, the advantages of having fewer interfering gases, slightly higher resolution, and better sensitivity to the coldest scenes compensate for the slightly lower information content in typical warm scenes. This is important because cold scenes are often associated with difficult-to-forecast weather (e.g., thunderstorms). In short, SWIR data appear to have roughly comparable forecast capability as LWIR data in suitable algorithms but present greater data assimilation challenges. These obstacles are worth overcoming, however, due to the potential forecast improvements that can be obtained in challenging cold conditions—and the significant cost advantages of a future spaceborne SWIR instrument.

Joao Teixeira considered the general problem of remote sensing of the planetary boundary layer from space. He showed that current observations from AIRS and from GPS satellite sounders provide important information on the coarse vertical structure of the atmosphere—e.g., boundary layer depth, temperature gradient heights, and water vapor content. GPS sounding techniques, on the other hand, have higher resolution and are not impacted by the presence of clouds—but cannot obtain independent information about temperature and water vapor. Competing boundary layer models predict differences in the vertical distribution of both temperature and water vapor, often in the presence of clouds, where IR sensors cannot sound. Teixeira argued that future space-based sounding instruments will need improved sensitivity and vertical resolution to answer important questions about model physics. (There was a Boundary Layer Sounding

[4] The 2017 Earth Science Decadal Survey, "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observations from Space," is available for download at *https://go.nasa.gov/2JdDHUz*. *Program of Record* refers to current Earth observations and those planned for the future regardless of whether the recommendations of the 2017 Earth Science Decadal Survey are implemented.

[5] NASA's Sounder SIPS is responsible for processing and reprocessing data products from two Suomi National Polar-orbiting Partnership (NPP) instruments: the Advanced Technology Microwave Sounder (ATMS) and the Cross-Track Infrared Sounder (CrIS), collectively referred to as the Cross-track Infrared and Microwave Sounding Suite (CrIMSS).

[6] These data can be viewed at *https://go.nasa.gov/3a1q1rI*.

Workshop held in September 2018, at which the topics discussed here were addressed in more detail.[7])

Chris Wilson [JPL] further described the ability of passive infrared sounders, e.g., AIRS, to measure water vapor vertical structure within the planetary boundary layer. He showed that these instruments have improved sensitivity to certain types of atmospheric structure, but that lower instrument noise and higher spectral resolution can improve the information content. He considered the AIRS, IASI, CrIS, and Tropospheric Emissions Spectrometer (TES)[8] instruments, and showed that all can provide an estimate of roughly the total amount of water vapor in the boundary layer.

Fall 2019 Sounder Science Team Meeting

In terms of overall content, the agenda for the fall Sounder STM was similar to that of the AIRS STM, with similarly named sessions. However, unlike the spring meeting—and unlike previous NASA sounder community meetings—the organizers intentionally changed the order of the sessions. The fall meeting began with talks about instrument calibration and radiance measurements (Level-1), rather than the traditional opening sessions featuring scientific interpretation of the retrieval (Level-2) record. The agenda included sessions organized as follows: Calibration and Level-1 Data, Retrievals and Validation, Sounder Science Team and Projects, Weather and Climate, Atmospheric Composition, and Applications.

While, in part, the agenda was set up this way to avoid scheduling conflicts with other meetings, the order of presentations also helped to underscore the importance of understanding the basic radiance measurements when interpreting retrieved quantities. This discussion led naturally into the Weather and Climate and Atmospheric Composition sessions that followed, where science results were discussed, and those built on the radiance measurements that had been covered earlier. Several attendees remarked that this agenda was more helpful in understanding the science results than was the traditional meeting agenda, where science results are presented first. The remainder of this section highlights several presentations given during the meeting. The reader is referred to the URL in the Introduction to view the full agenda and other presentations.

While the introductory presentations were presented on the second day of the meeting, they are described here first for consistency with earlier meeting reports. As in previous meetings, **Joao Teixeira** gave opening remarks and discussed plans for the AIRS Science Team. **Claire Parkinson** [GSFC—*Aqua Project Scientist*] described the status of the Aqua spacecraft and shared plans for the Aqua spacecraft to leave the "A-Train" and drift into a later local time sometime in 2022. As in earlier meetings, **Ruth Monarrez** discussed the Sounder SIPS at JPL and **Tom Pagano** described the status of the AIRS instrument. **Sid Boukabara** [National Oceanic and Atmospheric Administration (NOAA), National Environmental Satellite, Data, and Information Service (NESDIS), Center for Satellite Applications and Research] described NOAA's plans for next-generation space architecture, including sounders, extending to as late as 2040.

L. Larrabee Strow [University of Maryland, Baltimore County] described a new dataset that combines radiances from all AIRS, CrIS, and IASI instruments. The data are in a common format with quality control and well-characterized radiometric differences. Consistency will be achieved by placing all radiances on a common set of frequencies with common line shapes, referred to as a Level-1C (L1C) product. This dataset will include observations from current and planned infrared sounders, and will be a multi-instrument, multidecadal climate record of homogenized radiance. In addition, a radiative transfer model common to all instruments will be available with the L1C radiances to simplify retrieval algorithm development. Strow also reported that a unified retrieval algorithm supported by this record is being developed by other members of the NASA sounder community.

Joel Susskind [NASA's Goddard Space Flight Center] showed AIRS global mean surface temperature trends from the beginning of the Aqua record in August 2002 through August 2019—see **Figure** on page 35. He showed that the first eight months of 2019 were almost as warm as 2016—the warmest year on record, but also a year with a very strong El Niño. His results were consistent with those of independent NOAA and NASA researchers using *in situ* data sources. Susskind showed maps indicating that most of the warming in 2019 occurred poleward of 60° N. Given the well-established rapid Arctic warming, he speculated that 2019 would finish as the warmest year on record to date.

Baijun Tian [JPL] reported on a recently updated, publicly available observational dataset intended for testing in the Coupled Model Intercomparison Project (CMIP)—an international effort to improve projections of future climate. The dataset, called the Observations for Model Intercomparison Projects (Obs4MIPs), uses AIRS retrieved temperature and water vapor data from the troposphere and Aura Microwave Limb Sounder temperature and water vapor data from the upper troposphere and the stratosphere. The dataset is reported monthly on a one-degree latitude-longitude grid. He showed estimates of the Obs4MIPs sampling biases relative to model reanalyses data. The observed sampling biases largely arise from the inability of AIRS to observe below heavy cloud cover, and their estimation is an important part of the uncertainty analysis when evaluating CMIP models.

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[7] To read a summary of the Combined Boundary Layer Sounding Workshop, see "The 2018 NASA Sounder Community Update," in the March–April 2019 issue of *The Earth Observer* [**Volume 31**, **Issue 2**, pp. 30-32, 34—*https://go.nasa.gov/2U19jDa*].

[8] TES flies on NASA's Aura platform; it ended its mission in January 2018.

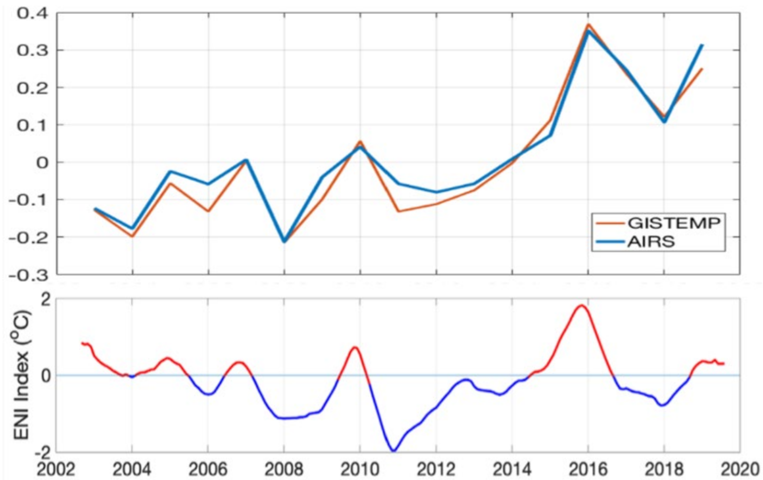

Figure. These graphs show the global mean surface temperature anomaly from September 2002 to August 2019, for AIRS on Aqua and Goddard Institute for Space Studies *in situ* temperature data (GISTEMP) [*top*] and the El Niño index for the same period [*bottom*]. Positive values roughly correspond to El Niño years and negative values with La Niña years. Rapid warming in 2019 is not associated with simultaneous El Niño onset. **Image credit:** Joel Susskind

Vivienne Payne [JPL] showed peroxyacetyl nitrate (PAN) retrievals from CrIS on Suomi NPP. She showed that PAN is important in tropospheric chemistry, particularly the chemistry of nitrogen oxide compounds, and that maps of CrIS PAN are similar to those retrieved from TES radiances. Payne also showed how CrIS retrievals compare well to *in situ* observations from the global Atmospheric Tomography Mission (ATom) and Western wildfire Experiment for Cloud chemistry, Aerosol absorption and Nitrogen (WE-CAN) aircraft campaigns.[9] Observations from the WE-CAN campaign demonstrate that CrIS is sensitive to PAN produced in wildfires.

Emily Berndt [NASA's Marshall Space Flight Center] gave an update on the use of hyperspectral infrared sounder retrievals in National Weather Service operations. This is part of an ongoing effort by NASA's Short-term Prediction Research and Transition Center (SPoRT) to transition NASA observations to operational applications. She started by demonstrating the use of AIRS ozone data to help predict surface intrusions of stratospheric air. Berndt also showed how the NOAA Unique Combined Atmospheric Processing System (NUCAPS), based originally on the AIRS retrieval system, was being used to help in identifying areas with very cold air aloft. These areas can lead to freezing of aviation fuel and are difficult to characterize in high-latitude regions where *in situ* observations are sparse. She also showed several examples of the use of NUCAPS data in severe-weather prediction over the Great Plains, including data provided by CrIS on NOAA-20.[10]

[9] ATom is a NASA Earth Venture Suborbital-2 mission to study the impact of human-produced air pollution on greenhouse gases and on chemically reactive gases in the atmosphere (*https://daac.ornl.gov/ATOM/campaign*). WE-CAN systematically characterized the emissions and first day of evolution of western U.S. wildfire plumes (*https://www2.acom.ucar.edu/campaigns/we-can*).

[10] When it launched in November 2017, NOAA-20 was known as the Joint Polar Satellite System-1 (JPSS-1) spacecraft; the name was changed shortly after launch when NASA (building the spacecraft and responsible for launch) handed control over to NOAA (responsible for operations).

Conclusion

NASA supports a sounder community that vigorously studies the remarkable datasets that have become available over the past two decades. The work by this community has led to significant improvements in weather forecasts, in climate monitoring, and in our understanding of the atmospheric processes that control both weather and climate. These improvements have been enabled by newer, more-detailed observations, especially over the past two decades. The improvements are achieved through analysis by a dedicated community of data users. The events described in this report provided an opportunity to share past and future challenges—first among which is interpreting an increasingly large and detailed set of observations of a complex and changing atmosphere. Progress toward this and other challenges were shared in the two meetings described in this report.

While much can be accomplished remotely in the year 2020, there is still value in having the community gather to discuss results and to coordinate future activities. The next AIRS STM had been scheduled for April 27-29, 2020, at the Beckman Institute at the California Institute of Technology in Pasadena, CA, where spring AIRS meetings have been held for over a decade. However, in light of recent developments surrounding the spread of the new Coronavirus and the restrictions associated with it, that meeting is now cancelled. A plan to organize a smaller virtual meeting, likely in late April or May, is under consideration. The annual NASA Sounder Science Team meeting in the fall will provide ample opportunity to present the most exciting recent results in sounder science, including AIRS. Check the AIRS website (*https://airs.jpl.nasa.gov*) for the latest updates. ■

NASA Selects New Instrument to Continue Key Climate Record

Stephen Cole, NASA Headquarters, stephen.e.cole@nasa.gov

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 has selected a new space-based instrument as an innovative and cost-effective approach to maintaining the 40-year data record of the balance between the solar radiation entering Earth's atmosphere and the radiation absorbed, reflected, and emitted. This radiation balance is a key factor in determining our climate: if Earth absorbs more heat than it emits, it warms up; if it emits more than it absorbs, it cools down.

The new instrument, named Libera, is NASA's first mission selected in response to the 2017 National Academies' Earth Science Decadal Survey.[1] It was selected competitively from four proposals considered under NASA's first Earth Venture Continuity (EVC-1) Announcement of Opportunity, released in 2018.

Introduced in the 2017 Earth Science Decadal Survey, EVC is a new category of investigation under NASA's Earth Venture Program element, which funds principal-investigator led activities that are competitively selected and cost- and schedule-constrained. The missions selected under EVC will focus on demonstrating innovative, low-cost approaches to maintaining targeted, unbroken, and consistent time series of measurements of key environmental parameters (e.g., radiation balance) that are important to studying climate change. The idea is to have a way to continue existing measurements over the long term.

The name Libera pays homage to the instrument's heritage. In Roman mythology, Libera was the daughter of Ceres, the goddess of agriculture. For NASA, Libera will be the "heir," or follow-on, to the highly successful series of Clouds and the Earth's Radiant Energy System (CERES) instruments[2] that currently make the radiation balance measurements that Libera will continue.

Libera will fly on the National Oceanic and Atmospheric Administration's (NOAA's) operational Joint Polar Satellite System-3 (JPSS-3), which is scheduled to launch by December 2027. The project's principal investigator is **Peter Pilewskie** [University of Colorado Laboratory for Atmospheric and Space Physics].

"This highly innovative instrument introduces a number of new technologies such as advanced detectors that will improve the data we collect while maintaining continuity of these important radiation budget measurements," said **Sandra Cauffman** [NASA Headquarters—*Acting Director of the Earth Science Division*].

Libera will measure solar radiation with wavelengths between 0.3 and 5 µm reflected by the Earth system and infrared radiation with wavelengths between 5 and 50 µm emitted from the Earth system as it exits the top of the atmosphere. The sensor will also measure the total radiation leaving the Earth system at all wavelengths from 0.3 to 100 µm. Libera also adds an innovative additional "split shortwave" channel measuring radiation between 0.7 and 5 µm to enable new Earth radiation budget science.

These wavelength ranges allow scientists to understand changes to Earth's climate system such as whether the planet is getting brighter or darker, and heating up or cooling down. The data will be available publicly following a brief checkout and commissioning period.

For more information about the Earth Venture program, visit *https://essp.nasa.gov*. ■

[1] The 2017 Earth Science Decadal Survey is available at *https://go.nasa.gov/2wj9W1G*; a PDF can be downloaded from *http://nap.edu/24938*.

[2] Both NASA's Terra and Aqua missions have two CERES instruments onboard. The joint NASA–NOAA Suomi National Polar-orbiting Partnership mission has a CERES instrument onboard, as does the NOAA-20 mission. A CERES instrument also flew on the Tropical Rainfall Measuring Mission, which launched in 1997; however, this instrument lasted for only eight months due to an onboard circuit failure.

Arctic Ice Melt Is Changing Ocean Currents

Rexana Vizza, NASA/Jet Propulsion Laboratory, rexana.v.vizza@jpl.nasa.gov
Matthew Segal, NASA/Jet Propulsion Laboratory, matthew.j.segal@jpl.nasa.gov

EDITOR'S NOTE: This article is taken from *nasa.gov*. While it has been modified slightly to match the style used in *The Earth Observer*, the intent is to reprint it with its original form largely intact.

A major ocean current in the Arctic is faster and more turbulent as a result of rapid sea ice melt, a new study from NASA shows. The current is part of a delicate Arctic environment that is now flooded with fresh water—an effect of human-caused climate change—see **Photo**.

Using 12 years of satellite data, scientists have measured how this circular current, called the *Beaufort Gyre*, has precariously balanced an influx of unprecedented amounts of cold, fresh water—a change that could alter the currents in the Atlantic Ocean and cool the climate of Western Europe.

The Beaufort Gyre keeps the polar environment in equilibrium by storing fresh water near the surface of the ocean. Wind blows the gyre in a clockwise direction around the western Arctic Ocean, north of Canada and Alaska, where it naturally collects fresh water from glacial melt, river runoff, and precipitation. This fresh water is important in the Arctic in part because it floats above the warmer, salty water and helps to protect the sea ice from melting, which in turn helps regulate Earth's climate. The gyre then slowly releases this fresh water into the Atlantic Ocean over a period of decades, allowing the Atlantic Ocean currents to carry it away in small amounts.

But since the 1990s, the gyre has accumulated a large amount of fresh water—1,920 mi^3 (8,000 km^3)—or almost twice the volume of Lake Michigan. The new study, published in *Nature Communications* (*https://www.nature.com/articles/s41467-020-14449-z*), found that the cause of this gain in freshwater concentration is the loss of sea ice in summer and autumn. This decades-long decline of the Arctic's summertime sea-ice cover has left the Beaufort Gyre more exposed to the wind, which spins the gyre faster and traps the fresh water in its current.

Persistent westerly winds have also dragged the current in one direction for over 20 years, increasing the speed and size of the clockwise current and preventing the fresh water from leaving the Arctic Ocean. This decades-long western wind is unusual for the region, where previously, the winds changed direction every five to seven years.

Scientists have been keeping an eye on the Beaufort Gyre in case the wind changes direction again. If the direction were to change, the wind could reverse the current, pulling it counterclockwise and releasing the water it has accumulated all at once.

"If the Beaufort Gyre were to release the excess fresh water into the Atlantic Ocean, it could potentially slow down its circulation. And that could have hemisphere-wide implications for the climate, especially in Western Europe," said **Tom Armitage** [NASA/Jet Propulsion Laboratory], lead author of the study.

Arctic sea ice was photographed in 2011 during NASA's Impacts of Climate on Eco-Systems and Chemistry of the Arctic Pacific Environment (ICESCAPE) mission—a shipborne investigation to study how changing conditions in the Arctic affect the ocean's chemistry and ecosystems. The bulk of the research took place in the Beaufort and Chukchi seas in summer 2010 and 2011. **Photo credit:** NASA/Kathryn Hansen

Fresh water released from the Arctic Ocean to the North Atlantic can change the density of surface waters. Normally, water from the Arctic loses heat and moisture to the atmosphere and sinks to the bottom of the ocean, where it drives water from the north Atlantic Ocean down to the tropics like a conveyor belt.

This important current is called the *Atlantic Meridional Overturning Circulation* and helps regulate the planet's climate by carrying heat from the tropically-warmed water to northern latitudes like Europe

continued on page 39

NASA Satellites Help Forecast Yellowstone Wildlife Migration

Abby Tabor, NASA's Ames Research Center, abigail.s.tabor@nasa.gov

EDITOR'S NOTE: This article is taken from *nasa.gov*. While it has been modified slightly to match the style used in *The Earth Observer*, the intent is to reprint it with its original form largely intact.

The bison population has really exploded over the last two decades in Yellowstone National Park. This creates complex situations for wildlife managers when the animals follow good grazing opportunities beyond the boundaries of the park and come into contact with surrounding communities. A NASA study has compiled and analyzed 20 years of data from the same sensor on two different NASA Earth science satellites to reveal a link between climate change effects on the productivity of grasslands and the proliferation of bison in Yellowstone. The work also shows how the same data, available in near-real time, can aid the park's conservation efforts by providing daily maps of green grass cover that help forecast the movements of bison.

The research project looked specifically at how long the growing season lasts in Yellowstone, from snowmelt in spring to first snowfall in autumn, and the vegetation that covers the land in between. The satellite data revealed that the season for vegetation growth has been getting longer, likely a result of climate change decreasing the severity of winters and warming average temperatures overall.

Studying national parks is helpful for this type of climate research, because human land use is restricted in these spaces. With little interference from people since Yellowstone was founded in 1872, scientists are better able to isolate climate change as a factor in any changes they observe there.

With the growing season getting longer across large areas of Yellowstone, the bison have had more opportunity to feed on grass, which has likely helped their population grow. But, as they pursue the best grazing spots throughout the season, they sometimes leave the protected area of the park. Tracking grassland growth can provide a clue to the bison's next move.

"It's complex—we found that the length of the growing season is changing quickly," said **Christopher Potter** [NASA's Ames Research Center], author of the study. "But, by compiling daily satellite data, we created a near-real-time online tool that resource managers can consult, much like a weather map."

The National Park Service originally approached NASA ten years ago, looking for insight into patterns of growth across Yellowstone's grasslands. At that point, there was enough long-term, daily satellite data to make a good start on meeting those needs, but to draw really confident conclusions about climate effects, scientists needed to look at a longer period.

An instrument called the Moderate Resolution Imaging Spectroradiometer (MODIS) now has a record 20 years long. Mounted aboard two different satellites (Terra, launched in 1999, and Aqua, launched in 2002), it has been able to view the entire surface of Earth not covered by clouds every day for two decades.

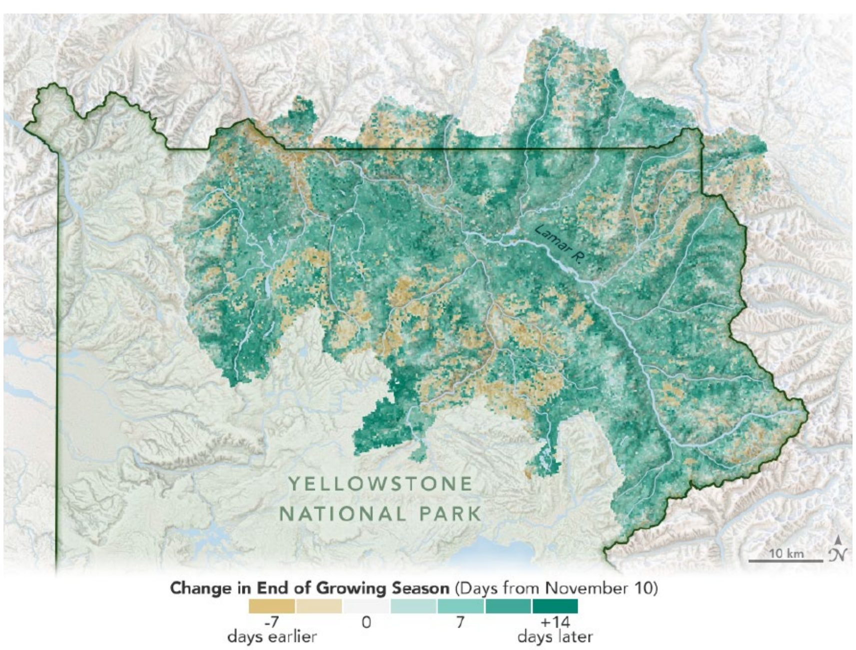

Figure. A study using 20 years of data from MODIS (combining data from Terra and Aqua) reveals that the season for vegetation growth has been getting longer in Yellowstone National Park. Likely a result of climate change decreasing the severity of winters and warming average temperatures overall, this effect on the productivity of grasslands has contributed to the growing number of bison in the park. **Credit:** Joshua Stevens/ NASA's Earth Observatory

For the climate study, Potter compiled data from this entire stretch—for the first time such a long run of daily updates has been compiled and analyzed for this National Park. With the data analysis performed, Yellowstone's wildlife managers can now check maps tracking the daily change in snow-covered area and the vegetation growth that follows. They'll use those data to try to anticipate where and when confrontations between bison and human communities are likely to happen and prepare the most appropriate conservation actions at the park boundaries.

Staying Ahead of Fire Season

The same concept can be used to help fight wildfires, and Potter is developing a similar system in Alaska. Across expanses of wilderness that are difficult to monitor, fire fighters have rarely had as much insight as NASA's satellite data can provide. When maps from the MODIS data show snow starting to melt and vegetation—which is fuel for fire—growing rapidly across the landscape, teams will know within a week's time where to stand ready to fight potential fires.

"MODIS is the silver bullet for these large-scale wilderness situations where daily updates make all the difference in planning a response," said Potter. "That's what it was designed for, and it's the only thing out there that can do it."

What's more, anyone can use the MODIS data this way. Like all data from NASA's Earth observing satellites, they are available for download from NASA's data centers and, with such a program to make daily comparisons of the measure of interest, these satellite data will have much to tell about America's wilderness. ■

Arctic Ice Melt Is Changing Ocean Currents

continued from page 37

and North America. If slowed enough, it could negatively impact marine life and the communities that depend on it.

"We don't expect a shutting down of the Gulf Stream, but we do expect impacts. That's why we're monitoring the Beaufort Gyre so closely," said **Alek Petty** [NASA's Goddard Space Flight Center], a co-author on the paper.

The study also found that, although the Beaufort Gyre is out of balance because of the added energy from the wind, the current expels that excess energy by forming small, circular eddies of water. While the increased turbulence has helped keep the system balanced, it has the potential to lead to further ice melt because it mixes layers of cold, fresh water with relatively warm, salt water below. The melting ice could, in turn, lead to changes in how nutrients and organic material in the ocean are mixed, significantly affecting the food chain and wildlife in the Arctic. The results reveal a delicate balance between wind and ocean as the sea ice pack recedes under climate change.

"What this study is showing is that the loss of sea ice has really important impacts on our climate system that we're only just discovering," said Petty. ■

NASA Earth Science in the News

Samson Reiny, NASA's Goddard Space Flight Center, Earth Science News Team, samson.k.reiny@nasa.gov

EDITOR'S NOTE: This column is intended to provide a sampling of NASA Earth Science topics reported by online news sources during the past few months. Please note that editorial statements, opinions, or conclusions do not necessarily reflect the positions of NASA. There may be some slight editing in places primarily to match the style used in *The Earth Observer*.

Scientists Will Soon Be Able to Monitor Air Pollution Hourly from Space, March 9, *theverge.com*. NASA, South Korea, and the European Space Agency (ESA) are working together on a "virtual constellation" of space-based instruments to document global air quality in unprecedented detail.[1] For the first time, scientists will be able to track pollution from space on an hourly basis. The first instrument to launch was South Korea's Geostationary Environment Monitoring Spectrometer (GEMS) on February 18, 2020, which flew into space mounted on a Korean satellite also tasked with ocean-surface monitoring. NASA plans to send a nearly identical instrument to space aboard a commercial communications satellite in 2022, it said in a briefing today. They'll be followed by ESA's two instruments that will join its existing air-quality-monitoring satellites, with the first taking off in 2023. The data they collect will boost efforts to rein in pollutants including nitrogen dioxide, smog, formaldehyde, and aerosols. Hourly data will better capture pollution that pops up episodically, e.g., rush-hour traffic or a power plant that increases its output to meet peak power demands. The satellite-mounted instruments will also be able to see whether pollution within a certain region was generated there or if it wafted from another country. "What's exciting is getting these pollution sources and pollution transport at different times of the day," said **Barry Lefer** [NASA Headquarters, Earth Science Division—*Tropospheric Composition Program Manager*]. "We'll be able to get more accurate air-quality [and] air-pollution forecasts because we'll know about the sources and how these sources change over time." Older space-based instruments have only been able to measure air pollution once a day. They pass over any given point on Earth at the same time each day, as they circle on a Sun-synchronous polar orbit. GEMS, by contrast, became the first air-quality sensor to view the Earth from geostationary orbit, which allows it—and eventually the other instruments in the constellation—to make constant observations of the same area.

Coronavirus: NASA Reveals how China's Lockdown Drastically Reduced Pollution, March 3, *forbes.com*. NASA released satellite images showing the impact the spread of the new ("novel") coronavirus (COVID-19) has had on dramatically reducing pollution throughout China. As China first began to battle COVID-19 in December, it led to an unprecedented drop in pollution in that country. Scientists first noticed the drop in pollution in Wuhan—where the new coronavirus was first identified. As coronavirus spread throughout Wuhan, Chinese officials stopped planes, trains, and subways, and heavily limited other vehicles. This decrease in vehicular traffic was the primary reason for the reduced pollution—an observation that was found elsewhere as the virus spread throughout China.[2] NASA and ESA used satellite images to detect how nitrogen dioxide (NO_2) changed over China since the beginning of the year. NO_2 gas is released by burning fossil fuels and is therefore a major pollutant from transportation and factories. Since the outbreak has led to reduced travel and shut-down factories, the levels of NO_2 have significantly decreased over China. **Figure 1** [*next page*] shows how NO_2 concentration changed from the period right before the Chinese government shut down transportation and factories compared to after the shutdown. The darker red areas show higher concentrations of NO_2, centered primarily on Beijing. The first reduction in NO_2 surrounded Wuhan; since then, it has spread across the country. NASA scientists note that this is the most dramatic drop they have ever seen in pollution across a country over a short time period.

***NASA Selects New Instrument to Continue Key Climate Record**, February 27, *spacedaily.com*. NASA has selected a new space-based instrument as an innovative and cost-effective approach to maintaining the 40-year data record of the balance between solar radiation entering Earth's atmosphere and the amount absorbed, reflected, and emitted. This radiation balance is a key factor in determining our climate: if Earth absorbs more heat than it emits, it warms up; if

[1] To learn more about plans for this constellation, read "NASA Ups the TEMPO on Monitoring Air Pollution," in the March–April 2013 issue of *The Earth Observer* [**Volume 25, Issue 2**, pp.10–15—*https://go.nasa.gov/2WGStuX*].

[2] Similar results have since been documented in South Korea, Europe, and the U.S. (see cover).

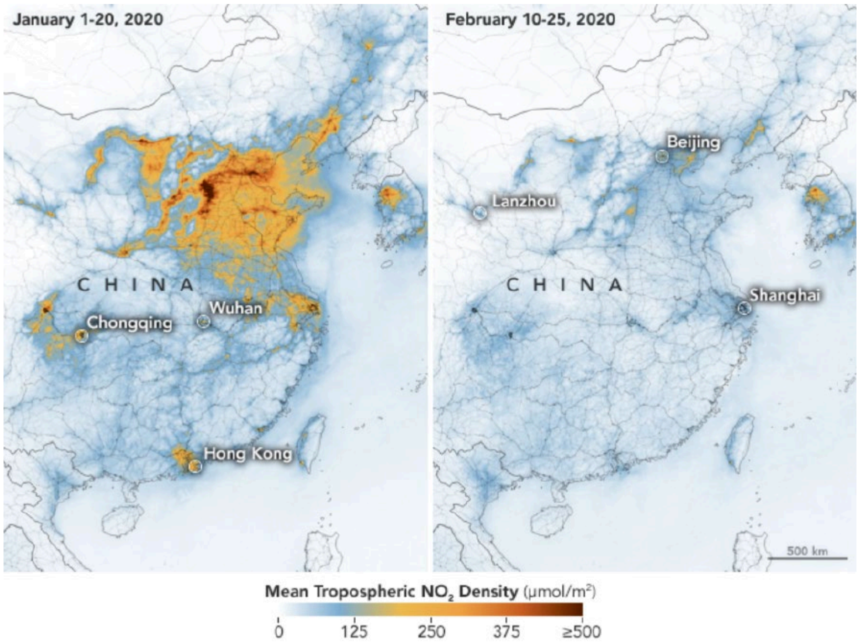

Figure 1. The maps above show concentrations of nitrogen dioxide (NO_2)—a noxious gas emitted by motor vehicles, power plants, and industrial facilities—across China from January 1-20, 2020 (before the Coronavirus quarantine) and February 10-25 (during the quarantine). The data were collected by the Tropospheric Monitoring Instrument (TROPOMI) on ESA's Sentinel-5 satellite. A related sensor, the Ozone Monitoring Instrument (OMI) on NASA's Aura satellite, has been making similar measurements. **Credit**: NASA's Earth Observatory

it emits more than it absorbs, it cools down. The new instrument, named Libera, is NASA's first mission selected in response to the National Academies' 2017 Earth Science Decadal Survey. "This highly innovative instrument introduces a number of new technologies, such as advanced detectors that will improve the data we collect while maintaining continuity of these important radiation-budget measurements," said **Sandra Cauffman** [NASA Headquarters—*Acting Director of the Earth Science Division*]. Libera will measure solar radiation reflected by the Earth system with wavelengths between 0.3 and 5 μm and infrared radiation emitted from the Earth system as it exits the top of the atmosphere, with wavelengths between 5 and 50 μm. The sensor will also measure the total radiation leaving the Earth system at all wavelengths from 0.3 to 100 μm. An innovative additional "split shortwave" channel, measuring radiation between 0.7 and 5 μm, has been added to enable new Earth-radiation-budget science.

"Antarctica Melts," NASA Says, Showing Effects of a Record Warm Spell, February 21, *npr.org*. Where there was a white ice cap, there are now brown blotches of land; melted snow and ice have created ponds of water. Those are the effects of the recent record high temperatures across sections of Antarctica, according to NASA, which on Friday released stunning before-and-after satellite images of the northern Antarctic Peninsula—see **Figure 2** [*next page*]. The images center on Eagle Island, part of the northern tip of the Antarctic Peninsula that stretches toward South America. Satellites took the images just nine days apart, on February 4 and February 13, 2020, showing the dramatic changes that took place in that time span. Two days after the first photo was taken, the area hit 18.3 °C (64.9 °F)—matching that day's temperature in Los Angeles, CA, NASA notes. "The warm spell caused widespread melting on nearby glaciers," the agency says. "Such persistent warmth was not typical in Antarctica until the twenty-first century, but it has become more common in recent years." On Eagle Island, the biggest loss of ice and snow came on February 6, when an inch of snowpack melted, according to NASA's climate models. By February 11, the island had lost four inches of snow. "I haven't seen melt ponds develop this quickly in Antarctica," glaciologist **Mauri Pelto** [Nichols College] said in NASA's news release about the phenomenon.

*__Arctic Ice Melt Changing Major Ocean Current__, February 21, *earthsky.org*. New research suggests that a major ocean current in the Arctic is faster and more turbulent as a result of rapid sea-ice melt, an effect of human-caused climate change. The current, called the *Beaufort Gyre*, has seen an influx of unprecedented amounts of cold, fresh water. It's a change, say the researchers, that could alter the currents in the Atlantic Ocean and cool the climate of Western Europe. The Beaufort Gyre is a wind-driven ocean current located

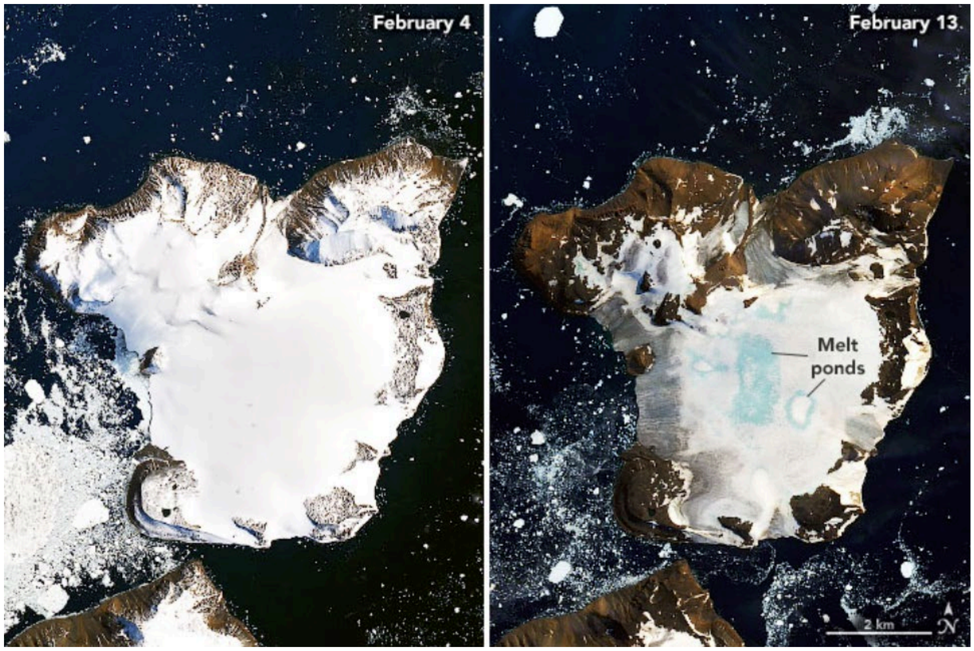

Figure 2. The images above show melting on the ice cap of Eagle Island and were acquired by the Operational Land Imager (OLI) on Landsat 8 on February 4 and February 13, 2020. **Credit:** NASA's Earth Observatory

in the Arctic Ocean's polar region. The gyre contains both ice and water, and accumulates fresh water by the process of melting the ice floating on the surface of the water. The study, published February 6, 2020, in the peer-reviewed journal *Nature Communications* (*https://www.nature.com/articles/s41467-020-14449-z*), used 12 years of satellite data to analyze how this circular current has been affected by the increase in fresh water from increased ice melting. In addition, persistent westerly winds have dragged the current in one direction for over 20 years, increasing the speed and size of the clockwise current and preventing fresh water from leaving the Arctic Ocean. This decades-long western wind is unusual for the region: Previously, the winds changed direction every five-to-seven years. The study's lead author, polar scientist **Tom Armitage** [NASA/Jet Propulsion Laboratory], said, "If the Beaufort Gyre were to release the excess fresh water into the Atlantic Ocean, it could potentially slow down its circulation. And that would have hemisphere-wide implications for the climate, especially in Western Europe."

*See News Story in this issue.

*Interested in getting your research out to the general public, educators, and the scientific community? Please contact **Samson Reiny** on NASA's Earth Science News Team at samson.k.reiny@nasa.gov and let him know of upcoming journal articles, new satellite images, or conference presentations that you think would be of interest to the readership of **The Earth Observer**.* ■

NOTE: *The Earth Observer* has temporarily suspended publication of its *Science Calendars*. In response to the ongoing COVID-19 pandemic and mandated social distancing most all NASA and International in-person meetings that had been scheduled for the next few months have either been cancelled or postponed. Some groups are rescheduling smaller online events; others are rescheduling in-person meetings later this year or in 2021. However, as of this writing the details are still rapidly evolving making it difficult to print a calendar at this time. We will resume publishing the calendar when the schedule becomes more settled.

List of Undefined Acronyms Used in Editorial and Table of Contents

ESA	European Space Agency
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
GSFC	NASA's Goddard Space Flight Center
LCLUC	Land Cover and Land Use Change
NASA HQ	NASA Headquarters
NOAA	National Oceanic and Atmospheric Administration
OCO-2	Orbiting Carbon Observatory–2
SARI	South/Southeast Asia Research Initiative
UV	ultraviolet

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Articles, contributions to the meeting calendar, and suggestions are welcomed. Contributions to the calendars should contain location, person to contact, telephone number, and e-mail address. Newsletter content is due on the weekday closest to the 1st of the month preceding the publication—e.g., December 1 for the January–February issue; February 1 for March–April, and so on.

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