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Statement of
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before the

Subcommittee on Commerce, Justice, Science and Related Agencies
Committee on Appropriations
U.S. House of Representatives

Chairman Serrano, Ranking Member Aderholt, Members of the Subcommittee, thank you for the opportunity to discuss NASA's contributions to understanding our planet and NASA's roles in advancing Earth system science and applications, including climate research. In this statement, I will also highlight some of the contributions made by NASA measurements, models, analyses, and NASA-funded investigators to the November 2018 Fourth National Climate Assessment, Volume II, which focused on climate impacts, risks, and adaptation in the United States.

The changing climate is having profound impacts and presenting profound opportunities – to us and to our adversaries. Global average sea level is rising, impacting our nation's extensive civil and national security coastal infrastructure, and the more than 100 million people worldwide who live within 1 meter of present-day sea level. Global average temperatures are rising, with the five warmest years on record having been the last five years, and 18 of the 19 warmest years ever measured having occurred since 2000. Changing temperatures are impacting agriculture, transportation, plants and human disease vectors. Rising ocean temperatures are contributing to widespread bleaching and death of corals in many regions and shifts in the distributions of economically important fish populations. The oceans are becoming more acidic, causing significant changes in ocean ecosystems. Diminishing sea ice cover is causing the Earth to absorb more heat from the Sun, perhaps leading to a positive-feedback cycle. Extreme weather events are becoming more frequent and more intense.

Not all of the changes are near-term negative. Growing seasons are increasing in present-day cool and cold areas, and previously frozen rivers and plains are becoming more habitable. But these changes may disproportionately benefit nations other than the United States. With generally warming temperatures, sea ice is diminishing, allowing more efficient Arctic

shipping routes and access to ocean floor resources for nations like Canada and Russia that have long Arctic coastlines and exclusive economic zones in the Arctic Ocean.

NASA measures and monitors these changes in our planet from space, and NASA uses the measurements to better understand the Earth's systems and the interactions between natural processes that define our environment.

The changing climate presents humans with profound responsibilities. We are the only species capable of altering present actions and making decisions based on our estimates of what our world will be like generations into the future. The Montreal Protocol – agreed to, and generally followed by virtually all nations – has been successful in reducing the concentrations of ozone-destroying chemicals like Freon in our stratosphere and setting the globe on a path likely to reduce the sizes and impacts of polar "ozone holes" and, by 2070, to return ozone levels and protection against harmful ultraviolet radiation to the high levels of the 1950s.

In part owing to significant advances by NASA and others over the past decades in understanding the Earth system, the greatest remaining quantitative questions about the future evolution of Earth's environment and climate stem from uncertainties regarding future economic, social, and policy decisions that humans will make.

NASA does not make policy recommendations. Rather, NASA research leads to greater understanding of our planet's natural processes, and the interactions of those processes, informing and improving Earth system models. NASA measurements provide information for policymakers, including information regarding the efficacy of environmental policies and decisions. *(For instance, NASA measurements of stratospheric ozone levels provide the information that policymakers need to determine whether the Montreal Protocol is working as intended.)*

Finally, the fact that we ***know with certainty*** that the climate is changing is a profound testament to our nation's – and to NASA's – technological and scientific abilities. NASA's comprehensive, global, sustained set of Earth observations and cutting-edge analyses allow us to monitor processes on and between the land, ocean, and the atmosphere. Thanks to NASA's satellite measurements and scientific analyses, we are increasingly able to detect climate trends and separate them from the much larger, shorter-scale, environmental variability we call "weather."

NASA research satellites and research activities are key for observing and understanding our complex Earth as an integrated system, making global measurements of many vitally important environmental indicators from the vantage point of space. Each of the examples of climate-scale trends – from changing sea levels and temperatures to changing atmospheric composition and global radiation balances – has been detected and quantitatively characterized by spaceborne observations.

NASA uses the spaceborne measurements from U.S. and international partner missions, along with airborne and ground-based measurements and cutting-edge scientific analyses, to

provide key insights and new understanding of the complex processes – and the many interactions between processes – that define the Earth and its environment. The quantitative knowledge we gain is infused into numerical models, which can then be used to predict future conditions and anticipate the effects of different scenarios and approaches.

Through our Applied Sciences program, NASA further combines measurements and understanding of the Earth derived from research to provide information required by stakeholders and other federal agencies and to develop and test focused information products that allow stakeholders and decisionmakers of all types to factor environmental information into their strategies and plans.

NASA's Capabilities for Observing and Understanding the Earth and its Changing Climate

NASA's Earth science and applications program is guided by the priorities of the 2007 and 2018 decadal surveys produced by the National Academies. NASA combines cutting-edge technologies with the unique vantage point of space, and advances integrative research, data analyses, and close connections with a broad range of government and private-sector user communities, to:

(1) Advance our knowledge of the myriad physical, biological, and chemical processes in and between the land, ocean, and atmosphere *and their interactions* that define our complex planet and its environment; and,
(2) Develop, test, and transition focused information products – based on spaceborne measurements and research-based understanding – to deliver societal benefit and inform and improve environmental decision-making by a broad range of stakeholders.

NASA does not make environmental policy nor does NASA have any regulatory authority in the area of Earth observation. NASA's role is to provide unique, comprehensive observations of our environment, to conduct research leading to greater understanding of the Earth, and to make the observations and the understanding available to governmental policymakers and decision-makers of all sorts.

To accomplish these goals, ESD pursues activities in four broad elements:

Flight Element: NASA's Earth science flight element develops, launches, and operates a fleet of Earth-observing satellites and instruments, acquiring measurements of many different environmental quantities from the vantage point of space. Only from orbiting satellites can we make measurements that have high spatial resolution and global coverage with uniform accuracy; that can regularly sample measurements at all locations for long periods of time; and that include enough observations of the wide range of ocean, atmosphere, and land variables to understand the connections between Earth system processes as well as the workings of the individual processes themselves. Only the vantage point of space allows measurements of the complex Earth system that can illuminate connections between short- and long-time scales, fine- and global-spatial scales, and chemical, physical, and biological processes.

NASA's Earth science orbiting fleet presently includes 22 Earth-observing satellite missions and major instruments, with another 14 missions and major instruments in development for launch between April 2019 and the end of FY 2022. During FY 2018, NASA launched five major Earth missions and instruments:

- Total and Spectral Solar Irradiance Sensor-1 (TSIS-1);
- Gravity Recovery and Climate Experiment Follow-on (GRACE-FO);
- ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS);
- Ice, Cloud and land Elevation Satellite-2 (ICESat-2); and,
- Global Ecosystem Dynamics Investigation (GEDI).

The next major Earth observing instrument will be the Orbiting Carbon Observatory-3 (OCO-3), scheduled for launch to the International Space Station (ISS) in late April 2019. The next Landsat mission, Landsat-9, is on schedule for launch in December 2020.

Most of the on-orbit and in-development NASA Earth-observing orbital missions involve significant international and interagency collaboration. The principal interagency collaborations for Sustainable Land Imaging involve the U.S. Geological Survey (USGS), and a NASA develops a range of instruments and satellites jointly with the National Oceanic and Atmospheric Administration (NOAA). The NASA-USGS Landsat satellites have been acquiring baseball field-sized (30-meter resolution) spaceborne measurements of the planet's land areas for more than 46 years, and the Landsat data are the longest continuous, consistently processed, global set of spaceborne measurements of land cover and land use change ever acquired.

NASA's Earth science flight element also develops and operates the data systems required for operating and generating standard products from the orbiting research missions, and for enabling cutting-edge, integrative research using the spaceborne observations. The 2018 Earth Science and Applications from Space Decadal Survey specifically examined and endorsed NASA's Earth science "Program of Record" missions presently in development for launch prior to 2023. NASA's flight element plan for new mission development in 2023 and beyond is explicitly consistent with the major decadal survey recommendations for new missions and instruments.

Research and Analysis (R&A) Element: Our R&A activities are focused on advancing comprehensive scientific understanding of our planet's processes and their interactions. By supporting data acquisition from all available sources (including domestic, private-sector, and international partner satellites; data from airborne, ship-based, and ground network instrumentation; and outputs from operational weather models), the R&A element enables scientists to investigate and solve large scientific questions that cannot be addressed using data from only a single mission or instrument. The R&A element redeems the nation's investments in the NASA satellite missions by using their measurements widely to address many scientific investigations and improve our understanding of the Earth and its systems.

The R&A activities are organized into six thematic focus areas:

- Climate Variability and Change;

- Water and Energy Cycle;
- Carbon Cycle and Ecosystems;
- Weather and Meteorological Processes;
- Atmospheric Composition; and,
- Earth Surface and Interior.

Each focus area is interdisciplinary. Each partially overlaps others, thus ensuring all aspects of the complex Earth system are covered. NASA's existing and future planned satellite fleet makes measurements of many of the ocean, atmosphere, land, and ice quantities required to advance Earth system science in each of the thematic focus areas.

The R&A element also supports development and sustained data acquisition from ground-based instrument networks, as well as plans and conducts land and ocean field campaigns involving ground-, aircraft-, and ship-based platforms, often with interagency and international partners. Data from the networks and field campaigns are used both to address scientific questions and to help calibrate and validate satellite products. Sustained, multi-year field and airborne efforts such as the IceBridge campaign to measure ice surface height and ice sheet changes in both Greenland and Antarctica have been used to make key observations between the launches of major satellite missions, and to acquire climate-relevant data that could not have been obtained from satellite instruments.

R&A investments also support: high-end computing for all of NASA; development and improvement of Earth system models on all scales, including global climate models; focused programs for early-career scientists; and rapid response activities to capitalize on scientific opportunities resulting from episodic and intermittent geophysical events and hazards such as volcanic eruptions and earthquakes.

Along with the Applied Sciences and Technology development activities described in the following sections, our R&A element identifies and funds the best, most innovative research. We issue competitive, broad solicitations for proposals – open to researchers in academia and the private sector, as well as state, local, and tribal governments and all federal agencies, including NASA. NASA's Earth Science Division manages approximately 1,700 competitively selected grants and contracts for science, applications, or technology.

Applied Sciences Element: NASA's Applied Sciences element connects measurements and understanding from the Flight and R&A elements with the need for environmental information by a broad range of generally non-technical decision-makers. Applied Sciences activities develop and test innovative uses of Earth observations and scientific knowledge to inform private- and public-sector planning and decisions. Our Applied Sciences activities focus on key societal development goals in water resources, disasters, health and air quality, and ecological forecasting. The element works closely with flight projects and potential users to promote early and substantive involvement of user communities in mission and data product design, ensuring that users are ready to leverage mission data soon after launch.

Collaborating with the U.S. Agency for International Development (USAID), NASA's Applied Sciences element conceived and originated the SERVIR program - a multi-national,

multi-regional, multi-agency, interdisciplinary effort to improve environmental understanding and decision-making, raise capacity levels in developing nations, and help rapidly address and assess damage from natural disasters that occur in the third world. Through SERVIR, NASA and USAID cooperatively provide funding support, strategic planning, and overall coordination for a network of hubs and activities to help developing countries manage resources, reduce risks, and improve security, extending American leadership around the world. NASA's Marshall Space Flight Center is the home of the SERVIR Coordination Office (SCO), which coordinates the development of new NASA scientific tools and their integration with existing analysis systems at the hubs, and provides global support to, and coordination of, SERVIR projects. In support of the global SERVIR effort, NASA has partnered with 19 U.S.-based research institutes across 14 states, and the SERVIR team has developed custom analysis tools in collaboration with a host of diverse institutions and trained a wide range of regional support staffers. SERVIR is just one example of the Applied Sciences element's national and global efforts to use environmental information to improve decision-making and the quality of life on our planet.

Through its Disasters Applications program, the Applied Sciences element promotes the use of Earth observations to improve prediction of, preparation for, response to, and recovery from natural disasters. Disaster applications and related research on natural hazards support emergency preparedness leaders in developing mitigation approaches, such as early warning systems, and providing information and maps to disaster response and recovery teams. In FY 2018 alone, the NASA Disasters Applications program arranged for and provided focused satellite data, flights of instrumented aircraft, damage analyses and risk assessments, and other environmental information to U.S. and international response agencies for:

- Earthquakes and tsunamis in Alaska, Indonesia, Japan, and Mexico:
- Wildfires throughout California;
- Floods and associated mudslides in Hawaii, California, and the Midwest, as well as in India and Laos;
- Eight major hurricanes and typhoons, including hurricanes Michael, Willa, Florence, and Lane; and,
- Volcanic eruptions in Hawaii, Ecuador/Galapagos, Guatemala, Indonesia, Papua New Guinea, and Vanuatu.

Earth Science Technology Office (ESTO) Element: NASA's ESTO element conducts Earth-focused technology development activities, including development and flight of technology demonstration CubeSats and development of advanced measurement approaches for the nation's future land imaging Landsat satellites.

ESTO identifies, matures, and tests a broad range of technologies, from components to instruments and including ground and on-orbit processing technologies, so that they can be used with low risk in the design of future ESD missions. This proactive approach to technology maturation avoids the costs and risks introduced when significant technology development is required to complete flight mission development. ESTO technology maturation investments are informed by and span the full range of new missions and measurements recommended by the Earth Science and Applications from Space decadal surveys.

ESTO-supported technology activities are fully competed, and are managed through four basic programs:

- The **Advanced Component Technologies** (ACT) program advances component- and subsystem-level technologies to reduce the risk, cost, size, mass, and development time of future missions and infrastructure. ACT brings instrument, platform, and information system components to a maturity level that allows their integration into other NASA-funded technology projects, such as those funded by the Instrument Incubator Program.
- The **Instrument Incubator Program** (IIP) fosters the development and assessment of innovative remote-sensing instrument concepts by assembling components into complete subsystems or even full prototype instruments for ground, aircraft, or engineering model demonstrations and characterizations.
- The **Advanced Information Systems Technology** (AIST) program supports innovative advances in on-orbit and ground processing technologies to generate, manage, and exploit data in the five- to 20-year horizon. The **In-Space Validation of Earth Science Technologies (InVEST)** program demonstrates and validates Earth science technologies through instrument flights on standardized CubeSat platforms launched as secondary payloads. InVEST allows rapid and cost-efficient risk reduction for selected new instruments and subsystems that could be incorporated into near-future Earth observing orbital missions and instruments. To date, seven InVEST technology demonstration missions have been launched, and four remain in operation. Following successful achievement of their technology goals, NASA continues to operate the InVEST satellites to make use of their valuable Earth observations.

Orbital Observing System Collaborations and Innovations

By hosting instruments on the ISS and on commercial satellites in geostationary and low-Earth orbit, flying satellites in close formation, and operating constellations of CubeSats and other SmallSats, NASA and our international partners are expanding the impact of our satellites and orbiting instruments beyond the simple sum of the measurements from individual spacecraft.

For more than a decade, the "A-Train," composed of six, different, relatively large, multi-instrument satellites, has been orbiting in formation, making near-simultaneous measurements of many different Earth system variables. All of the satellites pass over the same ground location in just over 10 minutes, some as close as 18 seconds apart.

An international collection of 10 satellites makes up the semi-heterogeneous Global Precipitation Measurement (GPM) constellation. Each GPM spacecraft carries at least one instrument that makes measurements over the globe related to rainfall and snowfall. Although the spacecraft are not flying close to each other, the orbits are coordinated and the measurements are cross-calibrated by periodic comparisons with the NASA-Japanese Space Agency's GPM Core Observatory. By combining observations from all of the satellites, we can for the first time in human history measure precipitation over the entire globe at a spatial resolution of 6-10 miles and a temporal resolution of a few hours.

In collaboration with NASA's Human Exploration and Operations Mission Directorate, ESD is flying Earth-observing instruments on the ISS, launching in the unpressurized compartments of ISS Commercial Resupply spacecraft and operating on external mounting points on the station. There are presently five ESD instruments operating on the ISS -- SAGE-III, LIS, GEDI, ECOSTRESS, and TSIS-1 -- with several more scheduled to launch by 2021, including OCO-3.

NASA is also flying homogeneous constellations of identical small satellites to make frequent measurements of important atmospheric quantities and air-sea interactions for storm and extreme weather event investigations and predictions. The CYGNSS constellation of eight SmallSats, launched in December 2016, makes frequent measurements of winds in the eyewalls of rapidly evolving hurricanes and typhoons, using GPS signals reflected from the sea surface. Future CubeSat constellations to make other atmospheric and radiation balance measurements are being developed for flight early in the 2020s.

Finally, we are building science instruments that will fly as hosted payloads on commercial satellites in geostationary and low-Earth orbits. The TEMPO and GeoCarb instruments will fly on commercial geostationary satellites and will measure air quality (TEMPO), and atmospheric carbon dioxide, carbon monoxide, methane, and solar-induced fluorescence (GeoCarb) over the Americas. The MAIA instrument, which will be hosted on a low-Earth orbiting commercial spacecraft, will measure aerosols. NASA's ESD is thus leveraging public-private collaborations and the use of geostationary satellites to observe the Earth just as NOAA has for many decades flown geostationary meteorological spacecraft for weather forecasting.

NASA's Dynamic Earth Science Partnerships

NASA's Earth Science Division engages in substantive partnerships and collaborations with other federal agencies, international agencies and coordination bodies, and private sector and commercial entities.

As noted above, NASA has decades-long Earth-observing space mission partnerships with NOAA and USGS. Data from NASA research satellites are provided in near-real-time to operational agencies (NOAA and DoD) to improve the accuracy of their environmental predictions. NASA and NOAA jointly developed the on-orbit Suomi-NPP satellite, which was launched in 2011 and served for a time as NOAA's primary polar orbiting meteorological satellite. NASA and USGS co-develop the Landsat satellite series, with NASA funding the design, implementation, and launch of the observatories, and USGS funding the on-orbit operations, ground processing, and data distribution systems. The Landsat collaboration continues with Landsat-9, on track for a launch at the end of 2020. NASA and USGS are co-leading architecture studies to define the design and approaches for the nation's spaceborne land imaging systems following Landsat-9. NASA is collaborating with NOAA on a similar major study on NOAA's future satellite architectures. These studies are considering the use of private sector satellites, international partners, and satellite disaggregation among other solutions.

More than half of the on-orbit NASA Earth research satellites, and a substantial fraction of the missions in development for launch over the next four years, involve significant hardware collaborations with international partners. Examples include the recently launched GRACE-FO with Germany, the upcoming NISAR synthetic aperture radar mission with India, and the Sentinel-6A/B ocean altimetry missions with the European Space Agency, NOAA, the European Commission, and the European meteorological consortium EUMETSAT. NASA ESD and the European Space Agency coordinate activities related to research and field campaigns, interoperable data systems, and joint satellite mission activities through the formal international Joint Program Planning Group. NASA also has satellite mission collaborations with the Japanese space agency JAXA, the French and German space agencies CNES and DLR, and the Canadian Space Agency among others.

In addition to hardware collaborations focused on specific space missions, NASA's ESD also plays leading roles in national and international coordination groups, such as the Congressionally mandated, 13-agency U.S. Global Change Research Program, the Office of the Federal Coordinator for Meteorology, both the domestic USGEO and international Group on Earth Observations (GEO), and the international Committee on Earth Observing Satellites (CEOS), which is the satellite coordination arm of GEO.

To advance Earth system science research goals, NASA relies on the DOE, USDA, and NOAA for critical in situ and airborne observations of greenhouse gases and carbon storage in soils and plants – and, of course, those agencies rely on NASA for high-quality ***global*** remote sensing products that extend the reach and resolution of existing sparse networks. Through sustained collaborations, we have improved understanding of the atmosphere and carbon cycle that can now inform decision-making and carbon management approaches.

In the area of interagency space data utilization, ESD plays a major role in the NOAA-NASA-U.S. Navy-U.S. Air Force Joint Center for Satellite Data Assimilation, which leverages multi-agency contributions to enhance the use of remotely sensed data in NOAA's and DOD's operational global and local numerical weather prediction systems. Similarly, the Short-term Prediction Research and Transition (SPoRT) project at Marshall Space Flight Center is a NASA- and NOAA- jointly funded activity to transition experimental and newly operational satellite observations and research capabilities to the local and regional operational weather forecast community. End users include NWS Weather Forecast Offices (WFOs), NWS/National Centers for Environmental Prediction (NCEP) National Centers, other government agencies, and private sector entities.

Beginning in FY 2017, in collaboration with USGEO, NASA helped develop the Satellite Needs Working Group (SNWG). The SNWG is an Executive Branch process to identify and evaluate the environmental information needs of all civil agencies. In SNWG, NASA identifies other-agency needs that can be substantially addressed by existing satellites and data products, as well as needs that will be addressed by planned upcoming missions. One example outcome of the SNWG process is the decision by NASA to modify the data acquisition plan for the upcoming NISAR mission to enable more frequent, moderate-resolution soil moisture measurements over the entire continental United States to support a range of agencies, including NOAA and USDA.

ESD is also engaging in new, innovative public-private partnership approaches with the private-sector, including both non-profit and for-profit organizations.

In a new partnership program begun by ESD in FY 2017, NASA has contracted with three commercial space firms to purchase Earth observing data acquired by commercial constellations of small satellites. In this pilot program, NASA does not set detailed data quality requirements. As part of the pilot activity, NASA researchers are evaluating and characterizing the commercial data products to determine their value for advancing ESD's research and applications activities. Upon positive completion of the pilot evaluation and discussions regarding costs, latency, and data rights, NASA may pursue long-term data buy contracts, thus benefitting both the government and the private sector space organizations.

NASA's Key Contributions to the National Climate Assessment

NASA is a key participant in the 13-agency, synergistic U.S. Global Change Research Program (USGCRP). Consistent with the requirements of the Global Change Research Act of 1990, the Fourth National Climate Assessment report (NCA4) was prepared and delivered in two volumes. The first, the Climate Science Special Report published in 2017, detailed how climate change is affecting the physical Earth system and documented the status and current knowledge of physical climate science. In November 2018, the second volume was released, documenting human welfare, societal, and environmental elements of climate change and variability for 10 regions of the United States and for 18 key national topics. This NCA4 Volume II focuses on observed and projected impacts, risks, and risk reduction approaches, and implications of climate change impacts under a variety of mitigation approaches.

As the nation's civil space agency and with substantial Earth science and applications research programs, NASA-funded research results and NASA personnel are foundational contributors to NCA4. NASA's observations, advanced Earth system models, and scientific analyses underpinned virtually all of the scientific findings in Volume I.

NASA also made substantial contributions to the NCA Volume II. Senior NASA ESD personnel served on the Subcommittee for Global Change Research and the NCA4 Steering Committee, both of which provided senior-level oversight of the preparation and review processes of the second volume. NASA detailed a scientist to serve in the NCA Coordination Office throughout the preparation of both volumes of NCA4, and a NASA researcher authored Chapter 11 ("Built Environment, Urban Systems, and Cities") of Volume II.

NASA analyses and research results are cited in NCA4 Volume II in many places. Imagery – including smoke-penetrating, high-resolution thermal infrared measurements – from NASA polar-orbiting research satellites has been instrumental in identifying and tracking the trends in the increasing number of western wildfires in recent years, and in understanding and predicting wildfire vulnerability.

NCA Volume II also used NASA-developed Earth system and climate models along with and sophisticated NASA multi-model analyses to quantitatively determine global temperature trends and their uncertainties over the past decade and to estimate contributions to the observed temperature evolution from different processes and sources, including from greenhouse gases.

Accurate and extensive rainfall, sea-surface temperature, and upper-ocean heat content measurements acquired from NASA's Global Precipitation Measurement Core Observatory satellite, the NOAA-NASA Suomi-NPP mission, altimetry satellites, and from NOAA's NASA-built operational geostationary GOES satellites, along with NASA-supported data analyses and research, informed the NCA4 summaries of observed recent changes in precipitation patterns from extreme storm events and their possible relationships to climate variations. High-resolution measurements of ground water and aquifer storage changes from the NASA GRACE (Gravity Recovery and Climate Experiment) mission informed the NCA4 Volume II analyses of groundwater impacts of the changing climate.

Going Forward

While uncertainties in predicting long-term future climate include our lack of knowledge of future human decisions, scientific questions remain regarding details of the feedback mechanisms between biogeochemical cycles and the physical environment, as well as more classical issues such as the physical modeling of cloud and water vapor feedback.

Sustained, accurate, space-based observations are providing critical information that is advancing Earth system science and enabling better resource management and decision-making. Only from space can we make measurements of most of the important quantities and link all of the important space and time scales. Ground and airborne observations, research activities, and technology advancement are increasing our understanding of our planet. NASA, NOAA, USGS, and other agencies must continue our collaborations to achieve these ends.

Thank you for the opportunity to discuss NASA's activities to observe and understand our complex Earth system on all scales. I would be pleased to respond to questions.