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Statement of
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Good morning Chairman Gordon, Ranking Member Hall and Members of the Committee. Thank you for the opportunity to appear today to discuss NASA activities in conjunction with other Federal agencies in the measurement and monitoring of atmospheric greenhouse gases and the exchange processes between the atmosphere, the oceans, and the land.

As the Nation's civil space agency and as a leader in Earth System Science, NASA develops and flies instruments and missions to measure greenhouse gases – and a host of other vitally important environmental quantities – globally, from the vantage point of space. Through our vigorous research program, NASA uses measurements from space, air, and land to advance our understanding of key natural processes that determine amounts, transports, and climate impacts of the greenhouse gases in the atmosphere, with particular attention paid to the ways in which these gases are exchanged between the air, the land, and the sea. The quantitative knowledge we gain through the measurements and research is codified in numerical models, which can then be combined with future measurements to provide predictions of future conditions and to anticipate the effects of different policies and mitigation approaches. Through our Applied Sciences program, NASA develops products that combine the measurements with the understanding to provide information required by stakeholders and in particular by other Federal agencies. Once developed and demonstrated by NASA, spaceborne measurement approaches can be used to monitor greenhouse gases and their impacts over the entire globe and for long periods of time. The satellite data, in conjunction with essential ground-based and airborne measurements acquired by many agencies and combined in an integrated, coordinated way, provide critical information related to verification and to the efficacy of policy decisions.

Greenhouse gases, and especially carbon dioxide (CO2), are extremely important components of the Earth system. They play key roles in determining the Earth's energy balance – how much of the incoming energy from the Sun is trapped within the Earth system of atmosphere, land, and ocean, and how much of that energy is re-radiated back out to space. In contrast with other greenhouse gas species which are broken down by chemical reactions in the atmosphere, CO2 is not destroyed; rather, the carbon is primarily cycled between the atmosphere, the surface layers of the ocean, and terrestrial vegetation over time scales of a few centuries. Therefore, decisions that we make today, and mitigation approaches that we take today, will still be determining conditions on Earth many generations into the future. As another consequence of long residence times and relatively rapid transport within the atmosphere, emissions originally localized at specific geographic locations influence environmental conditions around the entire globe. The distributions and concentrations of CO_2 and other greenhouse gases must thus be measured and predicted globally – a job that requires the global coverage and high spatial resolution of satellite measurements, combined with ground-based and airborne data and the use of comprehensive numerical Earth system models.

As will be discussed later in my testimony, we know beyond a doubt that over periods of a few years, about half of the CO_2 emissions remain in the atmosphere and the remainder of the emitted CO_2 is removed from the atmosphere and goes into the ocean and the land for long time periods. While the localized magnitudes of these natural exchange processes are small, their overall impacts can be considerable when accumulated over huge areas such as boreal forests and the oceans. While we know the global net effects of these exchanges over time scales of a few years, we must make and analyze new measurements of near-surface atmospheric greenhouse gas mixing ratios and land use/land cover conditions in order to understand the details of the processes, and to be able to make accurate predictions as to how the processes will change as the Earth's climate evolves.

Make no mistake about it, however: the measurements of greenhouse gases that are necessary to accurately define important, spatially extensive, natural atmosphere-land and atmosphere-ocean exchange processes are difficult to make and require the Nation's cutting edge technological as well as scientific skills. The benefits, however, are immense. Coupling our present extensive knowledge of emission inventories with new information and understanding we will gain on the magnitudes and uncertainties of natural and human-induced fluxes from land use changes and management practices will not only provide additional information to support policy development and evaluation, but also may identify additional areas for mitigation efforts and lower the cost of compliance.

NASA's Existing Capabilities for Measuring Carbon

Climate encompasses more than Earth's physical climate and physical observations. Greenhouse gases include carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFCs), nitrous oxide (N_2O), ozone, and water vapor. These gases play key roles in climate change, which involves the biogeochemistry of Earth's atmosphere and biosphere (land and ocean). NASA's satellites, along with coordinated in situ and remote sensing networks and airborne science programs established and operated by many other agencies, help to quantify, characterize, and improve the accuracy and precision of greenhouse gas measurements over the land, as well as in the atmosphere and ocean. NASA ground-based networks provide critical long-term data for the validation of remote observations and contribute to national and international observational databases. NASA modeling activities along with measurements synthesize our understanding of the importance of greenhouse gases to climate change. While NASA does not have an operational aspect to its mission for monitoring practices, NASA data are utilized by partners in other agencies for operational activities.

Given the importance of understanding how CO_2 cycles through the environment, the NASA Earth Science Division maintains a vigorous research program through its carbon cycle and atmospheric composition focus areas to study the distribution and the forces determining the atmospheric concentrations of carbon dioxide and other key carbon-containing atmospheric gases (especially methane), as well as carbon-containing aerosols. Data from NASA satellites are studied, and observations are also made from airborne platforms and surface-based measurements in ways that can be used to validate and complement space-based observations. Satellite data are obtained for land cover and terrestrial and oceanic productivity, as these are critical in providing quantitative information about the distribution of the biosphere and the biospheric activity that exchanges carbon-containing gases between the land, ocean surface and the atmosphere. They can also provide critical information about the distribution and impact of fires, which play an important role in adding carbon-containing (and other) trace gases into the atmosphere. Models are then used to assimilate observations to produce accurate yet consistent global data sets, to infer information about sources and sinks, and to simulate future concentrations of atmospheric greenhouse gases that contribute to, and are affected by, climate change.

Through a series of direct measurements and models, NASA helps to characterize and quantify greenhouse gases and related controlling processes in the terrestrial, near-surface aquatic, and atmospheric environments. Data from the Atmospheric Infrared Sounder (AIRS) on the Aqua spacecraft delivers ozone, water vapor, methane, and CO2 concentrations. The Aura spacecraft's Tropospheric Emission Spectrometer (TES) provides information on ozone, CO2, methane, and water vapor, while its Microwave Limb Sounder (MLS) provides ozone, nitrous oxide, and water vapor mixing ratios and the Ozone Monitoring Instrument (OMI) measures Nitrogen Dioxide (NO2), ozone, Sulfur Dioxide (SO2), and aerosols. However, the policy and science issues associated with methods for enhancing carbon uptake in forest and agricultural land, and with spatially extensive air-land/air-sea exchange processes, require accurate measurements near the surface. Because of the techniques used to make the measurements, both the AIRS and the TES CO2 data correspond to upper-level concentrations (above about 13,000 to 36,000 feet), while the MLS measurements correspond to even higher levels in the stratosphere. Had the Orbiting Carbon Observatory (OCO) been successful, the combination of its accurate *surface* CO2 measurements and the upper-level *profiles* obtained by AIRS would have provided a valuable component of a global data acquisition capability.

The NASA airborne fleet can detect and help quantify all of the aforementioned greenhouse gases in the atmosphere. For the ocean, Moderate Resolution Imaging Spectrometer (MODIS) data from the Terra and Aqua spacecraft can be used to estimate CO2 exchange between the ocean and atmosphere. MODIS data are also used to estimate annual carbon uptake by terrestrial and aquatic vegetation over broad regions.

These observations are particularly powerful when the measurements from multiple assets are combined. One recent example of NASA's activity in this area is the Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) field campaign carried out in the spring and summer of 2008. In the ARCTAS campaign, data from three NASA aircraft based in Canada and Alaska, making flights as far away as Greenland, studied the gas phase and particulate composition of the troposphere, emphasizing their distribution in the atmosphere over North America and the Arctic. In particular, in the summer campaign, numerous observations of air affected by forest fires were made. By combining data from aircraft and satellites, scientists are now better able to understand the regional scale impacts of fires and long-range pollutant transport on air quality and the implications for climate.

Within planned future missions, the Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI) mission, and to a lesser extent the Ice, Cloud, and land Elevation Satellite-II (ICESat-II), will contribute to improved estimates of above-ground carbon storage in vegetation that can be used to monitor the activity of forest carbon sinks and quantify carbon losses from them to the atmosphere due to major disturbances (storms, harvest, fire, etc.). Among later Decadal Survey-recommended missions presently under study, the Active Sensing of CO2 Emissions Over Nights, Days, and Seasons (ASCENDS) mission will measure CO2, the Geostationary Coastal and Air Pollution Events mission (GEO-CAPE) will measure ozone and CO2 exchange between atmosphere and ocean, the Aerosol-Cloud-Ecosystems (ACE) will be used to estimate annual carbon uptake by aquatic vegetation, and the Global Atmospheric Composition Mission (GACM) will measure ozone, water vapor, and aerosols.

The NASA Earth Science Research Program goals in carbon cycle science are to improve understanding of the global carbon cycle and to quantify changes in atmospheric CO_2 and CH_4 concentrations as well as terrestrial and aquatic carbon storage in response to fossil fuel combustion, land use and land cover change, and other human activities and natural events. NASA carbon cycle research encompasses multiple temporal and spatial scales and addresses atmospheric, terrestrial, and aquatic carbon reservoirs, their coupling within the global carbon cycle, and interactions with climate and other aspects of the Earth system. The primary disciplinary research programs that support carbon cycle science at NASA are conducted within its Carbon Cycle and Ecosystems, and Atmospheric Composition focus areas (including the Upper Atmosphere, Tropospheric Chemistry, Atmospheric Chemistry Modeling, analysis, and Prediction, Ocean Biology and Biogeochemistry, Radiation Sciences, Terrestrial Ecology, Land Cover/Land Use Change, the Modeling Analysis and Prediction, Interdisciplinary Science, Carbon Cycle Science, Ozone Trends, Earth Observation Satellites Science, Aura Science programs, and to some extent, Physical Oceanography programs).

A focus on observations from space pervades carbon cycle research by NASA and is a basis for partnerships with other U.S. Government agencies and institutions. NASA carbon cycle research contributes toward the goals of major U.S. Climate Change Science Program (CCSP) activities, including the U.S. North American Carbon Program (NACP) and the Ocean Carbon and Climate Change Program (OCCC).

As an example, NASA working with other agencies and Departments under the NACP is working to improve estimates of carbon storage in forests and the impacts of disturbance (fire, insects and pathogens, severe storms, etc.) on this carbon storage. Other NASA NACP studies are developing regional carbon budgets, documenting year-to-year variations in sources and sinks, and attempting to attribute those changes to particular factors. Other NASA satellite studies are documenting changes in growing season length and the occurrence of critical seasonal events in ecosystems (e.g., budburst, flowering, leaf fall, algal blooms) that also affect carbon dynamics. All of these studies are advancing our scientific understanding and monitoring capacity – as well as advancing our abilities to evaluate the carbon cycle implications of land management practices.

NASA research has also focused on developing the scientific foundation for sound decision making with respect to climate policy and the management of carbon in the environment. NASA's current and future well-calibrated measurements from space facilitated by NIST standards, in combination with decades of scientific understanding achieved through such studies, and the Agency's experience in demonstrating new decision support capability put NASA in a strong position to contribute to the Nation's responses to climate change. NASA's global observations and global modeling capabilities also will help to reduce regional and global climate and carbon cycle science model uncertainties.

The NASA Applied Sciences Program projects extend the products of Earth science research and the tools associated with that research, including observations, measurements, predictive models, and systems engineering, to meet societal needs beyond NASA Earth Science Research Program objectives. The Applied Science Program also addresses carbon management. For example, projects exploit NASA carbon cycle research results and related capabilities to enhance decision making within agencies responsible for resource management and policy decisions that affect carbon emissions, sequestration, and fluxes among terrestrial, aquatic, and atmospheric environments.

NASA can provide its research observations, well-calibrated and well-validated for assessment and quantification of greenhouse gases and of aggregate changes in carbon sources and sinks on the land and in the ocean. Space-based measurements of greenhouse gases in the atmosphere are available now, albeit limited in utility, and will only improve in the future (with potential recovery from OCO and future development of ASCENDS, and ACE). Current observations of land cover, vegetation dynamics and ocean color, as well as numerous climate variables, allow for the identification and characterization of terrestrial and aquatic carbon sources and sinks as well as for attribution of some of the processes controlling their dynamics. Future observations of vegetation canopy height profiles will demonstrate and prove new abilities to support the estimation of carbon sequestration in forests.

The Role of the Orbiting Carbon Observatory (OCO)

On February 24, 2009, NASA's Orbiting Carbon Observatory (OCO) failed to reach orbit after liftoff from Vandenberg Air Force Base in California due to a launch vehicle mishap. This mission was designed to make near-global measurements of atmospheric carbon dioxide mixing ratios (approximately equivalent to the CO2 concentration in a vertical column of the atmosphere) over the sunlit hemisphere of the Earth. The OCO measurements were designed to have high precision and dense spatial sampling. Indeed, OCO was designed to make the most challenging atmospheric trace gas measurements ever made from space.

The OCO measurement approach was designed to be most accurate in the lower troposphere close to the air-sea and land-air interface, which is where the transfers of atmospheric CO2 to the ocean and the terrestrial biosphere take place. OCO was thus optimized to allow study of the CO2 transfer processes, and quantification of the spatially extensive, regional-scale (several hundreds of miles in extent) sources *and sinks* of carbon in the natural system, and to allow their monitoring on seasonal time scales. To accomplish these tasks, OCO was designed to measure total column CO2 with a precision of almost one part per million (ppm), spatial resolution less than one mile for instantaneous measurements, and a sampling pattern (a combination of orbit and swath width) that allowed global coverage on approximately monthly time scales. The on-orbit measurement strategy for OCO would have allowed accurate data to be obtained both over land and over the harder-to-measure, but larger, areas of the global oceans. The relatively small spatial footprints (high resolution) would have allowed measurements through clear-sky regions even in the presence of broken clouds. The OCO measurements would have been more accurate, had higher spatial resolution, and had greater coverage than those of any other existing spaceborne trace gas measurement system. A comprehensive validation activity was planned and funded as part of the OCO mission. Using precisely calibrated measurements from upward-looking, ground-based instruments in the multi-agency Total Carbon Column Observing Network (TCCON) along with auxiliary information from NOAA, NSF, and other agency programs, residual errors in the OCO measurements were to have been identified and removed, resulting in a calibrated OCO data set referenced to the World Meteorological Organization standard. Indeed, the OCO mission activity has contributed three of the primary TCCON sites (Park Falls, Wisconsin; Lamont, Oklahoma; and Darwin, Australia) in this global network.

As a research, science, and technology demonstration agency, NASA rarely plans from the start to build multiple copies of instruments or missions. Given the importance of making multiple simultaneous measurements of many different quantities in order to understand the interactions between processes that define the Earth as a complex but integral system, the NASA Earth Science Division has historically focused on breadth of missions and measurements, rather than building multiple copies of instruments and missions in order to proactively assure rapid replacements in the event of launch catastrophes or early mission failures. Indeed, our careful design, construction, and extensive testing at every step of the process have resulted in spectacular success rates and long lifetimes for many of our Earth missions.

Prior to February 24, 2009, NASA had neither plans nor resources to build a replacement mission, either as a "carbon copy" of OCO itself or as a functional equivalent mission or instrument.

Following the launch failure, the NASA science and engineering teams have been actively investigating recovery from many different approaches. From the start, NASA has ensured that the OCO Science Team, augmented with researchers from our Research and Analysis programs and international scientists, have been kept intact and funded to investigate the state of carbon cycle science, whether the present key issues should or must be addressed through space-based measurements, and whether a new space mission was warranted in light of the present on-orbit assets of NASA and our international partners.

On April 9, 2009, the science team's thoughtful, well-documented white paper was completed. The science team concluded that an OCO reflight or a functionally equivalent mission is necessary to advance carbon cycle science and to provide the basis for thoughtful policy decisions and societal benefits. Based on this scientific foundation (and working in parallel with the science analyses, anticipating the result), NASA tasked the engineering teams to examine several options for rapid mission implementation. The Team identified the top three candidate approaches as: (1) rebuilding an OCO mission with as few changes as possible and launching the so-called "Carbon Copy" into its planned orbit as an element of the "A-Train," the constellation of five U.S. and international satellites flying in close formation to make a "virtual observatory" with highly synergistic, near-simultaneous measurements; (2) combining a near-copy of the OCO instrument with a Thermal Infrared (TIR) sensor on a single spacecraft, to be launched into close constellation with the Landsat Data Continuity Mission (LDCM), presently under construction for launch in December 2012; and (3) building a near-copy of the OCO instrument for launch to and flight on the International Space Station (ISS).

Each of these options has challenges, ranging from electronic parts obsolescence which preclude any complete identical rebuild of the OCO instrument and spacecraft, to significantly degraded coverage from the ISS orbit and the need to provide a dedicated pointing mechanism for the OCO instrument, and accommodation issues associated with the flight of both a TIR and an OCO-like instrument on the same spacecraft. There are also advantages to each of these approaches, which help offset the challenges described above, including early launch availability and relative simplicity for the "Carbon Copy," possible lower launch costs and servicing potential for the ISS flight, and chances for an LDCM launch to allow more overlap than otherwise possible with the now-ancient Landsat-7 and Landsat-5 missions, while still providing synergistic multispectral and thermal infrared measurements within about 6-12 months after the LDCM launch.

At present, our understanding of the Carbon Copy option is most mature, while the OCO/TIR combined mission is being studied vigorously to refine its parameters. The scientific degradations associated with the flight of OCO on the ISS discourage near-term focus on this option. It is our objective to have solid technical and programmatic understandings of both the Carbon Copy and combined OCO/TIR missions by the end of May.

In parallel with NASA investigation of OCO reflight options, we have been collaborating substantively with our Japanese colleagues to expand and accelerate previously planned U.S. contributions to the validation of GOSAT/IBUKI CO2 measurements and to utilize GOSAT/IBUKI data to help refine existing high-level OCO algorithms. While the accuracy and sampling characteristics of GOSAT/IBUKI are insufficient to allow key OCO science and policy questions to be addressed adequately, the use of the GOSAT/IBUKI measurements to help refine OCO algorithms now will accelerate the production of quality products from a future mission.

It should be noted that one of the mid-term missions that the Decadal Survey recommended for NASA to develop was a laser-based, carbon dioxide-measuring mission called "ASCENDS" (Active Sensing of CO2 Emissions over Nights, Days, and Seasons). Using active lasers rather than reflected sunlight, ASCENDS is expected to provide CO2 measurements in polar regions during the winter and at night. Technology development advances required for the lasers on ASCENDS preclude its early flight within the next three years. Furthermore, the use of reflected sunlight for OCO measurements (versus the active lasers for ASCENDS) makes the smaller and simpler OCO-like instrument attractive for long-term monitoring of near-surface CO2 levels and offset processes.

We will keep the committee informed as we develop the technical and programmatic understanding necessary for future decisions on OCO recovery options and their associated budget implications within the broader context of other Earth Science priorities.

Working With Our Interagency Partners

U.S. interagency programs provide the fora for coordination of the respective agency activities. These bodies include the CCSP Program Office, the Climate Change Technology Program, the U.S. Ocean Action Plan committees, and U.S. Group on Earth Observations (U.S. GEO). The majority of the collaborations and coordination are achieved through informal interagency interactions among the program managers and scientists that are responsible for the aforementioned research efforts. There are important interdependencies that both require and challenge interagency coordination. NASA relies on the Department of Energy, the United States Department of Agriculture, and the National Oceanographic and Atmospheric Administration for critical in situ and airborne observations of greenhouse gases and carbon storage in soils and plants – and, of course, they rely on NASA for calibrated, validated remote sensing data products. Together, we have developed vastly improved understanding of the atmosphere and carbon cycle to go with those measurements that can now be applied to the development of climate policy and carbon management.

Internationally, partnerships are made in many fora, examples include Global Earth Observation System of Systems (GEOSS), the Committee on Earth Observing Satellites (CEOS), the Global Carbon Project, the World Climate Research Program, and other IGBP and UNEP-WMO programs. International bilateral meetings are also helpful for the international coordination.

The academic research community and federal efforts are mainly coordinated by the program managers in the Earth Science Division, who take great strides at NASA among flight programs, research, and applied sciences to ensure the research community and management communities provide feedback to the overall efforts of the NASA Earth Sciences Division. The National Research Council of the National Academies of Sciences has provided valuable inputs from the community regarding future research directions for NASA (e.g., the recent Decadal Survey). NASA also listens closely to its advisory subcommittee and the Science Steering Groups associated with the U.S. Carbon Cycle Science Program, the North American Carbon Program, and the Ocean Carbon and Biogeochemistry Program.

Going Forward

Uncertainty of climate for the 21st century is driven as much by our inability to quantify the feedback between biogeochemical cycles and climate change, as it is by uncertainty in the physical modeling of the cloud and water vapor feedback or economic projections of fossil fuel emission. These uncertainties in the feedback processes result in large differences in the predictions of climate models. At present, even for fixed, prescribed fossil fuel emission scenarios, the predicted atmospheric CO2 levels in 2100 from the best coupled carbon-climate models differ by more than 300 ppm, which is equivalent to about 40 years of present anthropogenic CO2 emission levels (e.g., *Freidlingstein et al., J. Climate,* ***19*** *(2006), 3337-3353)*.

Space-based observations sustained over a long period of time at the current level of quality or better are critical to improving the science of climate change and enabling better resource management and decision making. Well-calibrated in situ and airborne observations for validation and for study and diagnosis of process controls, complementary research activities, as well as technology advancement, are necessary to improve observational capabilities. NASA, NOAA, NSF, and USGS must continue and enhance their collaborations to achieve these ends.

Thank you for the opportunity to discuss NASA activities in the measurement and monitoring of atmospheric greenhouse gases and the exchange processes between the atmosphere, the oceans, and the land. I would be pleased to respond to any questions that you or the other Members of the Committee may have.