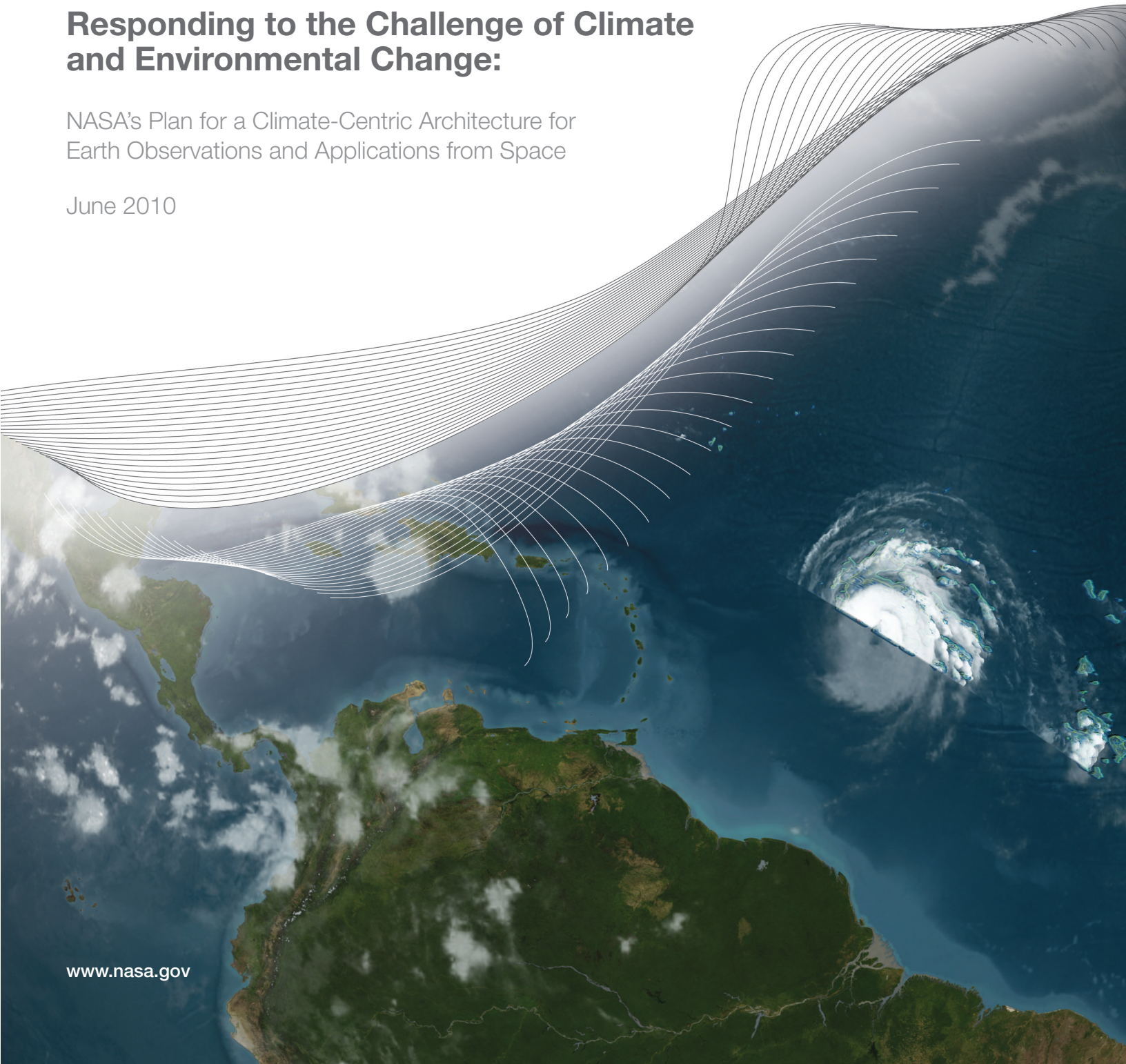
National Aeronautics and Space Administration

Responding to the Challenge of Climate and Environmental Change:

NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space

June 2010



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Executive Summary

The Obama Administration is acting on its recognition that climate change is a defining issue of our generation. Our responses to the challenges of climate change—accurate prediction, equitable adaptation, and efficient mitigation—will influence the quality of life for the nation, and indeed the world, for generations to come. The President's FY2011 budget request provides a cumulative $10.3 Billion (B) funding to NASA's Earth Science program over the period FY2011–2015 to address pressing scientific and national issues associated with climate change and the nation's climate research and monitoring capabilities. As recommended by the National Research Council's (NRC's) Earth Science and Applications Decadal Survey, this FY2011 budget request returns NASA Earth Science funding to the approximate level that it had in FY2000, an increase of more than 30% from recent levels. This funding allows for the acceleration and expansion of activities across the entire, coordinated Earth Science program—in the areas of flight missions, research, applications, and Earth Science mission technology development—thus advancing the balance and scope that have been hallmarks of NASA Earth System Science. This document outlines the integrated NASA Earth Science program enabled by the FY2011 budget request.

The integrated and balanced program described here is aligned with the Administration's overarching emphasis on climate research and monitoring. It is further consistent with, and has been informed by, the comprehensive vision for NASA's Earth Science endeavor set forth by the NRC in its Decadal Survey. Most visibly, this architecture revitalizes the nation's research satellite system, providing near-term measurements to advance science, underpin policy, and expand applications and societal benefits. In addition to building the Orbiting Carbon Observatory-2 mission for launch in 2013, NASA will: accelerate development of the four NRC Decadal Survey Tier 1 missions so that they are all launched by 2017; accelerate and expand the Venture-class line of competed, innovative small missions; initiate new space missions to address continuity of high-priority climate observations; and bring two Decadal Survey Tier 2 missions forward to allow launch by 2020.

Complementing the flight portfolio expansion, NASA will advance climate research, multiply applications using the full set of available (NASA and non-NASA) satellite measurements for direct societal benefit, and develop/mature technologies required for the next generations of Earth observing missions. These non-flight activities, which are essential for transforming the global spaceborne measurements into accurate predictions, efficient information products for the broad range of end-users, and consistent bases for long-term monitoring, include (but are not limited to): modeling and assessments supporting National Assessments and future IPCC studies; acceleration of operational use of NASA research products for predictions, building on expertise developed with systems such as SERVIR; focused calibration activities to effectively leverage measurements from international space missions and *in-situ* observations; development and testing of aspects of a national carbon monitoring system serving science, policy-makers, and stakeholders; and investments in effective Earth Science education programs such as GLOBE.

With this plan, NASA's Earth Science program will substantially advance science, expand applications, and address national information requirements for near-term policy development and future evaluations of policy efficacy.

To present the next level of detail, the work to be accomplished with FY2011 President's Budget Request is described in the categories of *Space-based Observing Systems; Mission-enabling/Data Exploiting Research and Applications; and Assembling the Components to Meet National Needs.*

1. Space-based Observing Systems:

The FY2011 President's Budget Request allows significant expansion of, and launch date acceleration for, the suite of NASA-developed Earth observing satellite missions. The budget thus enables NASA to address a major finding of the NRC's 2005 Decadal Survey interim report: the crisis of a contracting and aging US environmental research satellite constellation. The following missions are either accelerated or initiated by this budget.

Orbiting Carbon Observatory-2: Funding is provided for rapid development and launch of OCO-2 (2/2013). Additional climate monitoring and research funding enables development of a second set of instrument hardware for use, following a successful OCO-2 launch, as an instrument of opportunity in a future carbon monitoring mission.

Accelerated Decadal Survey Tier 1 Missions: The FY2011 budget request enables all four Tier-1 Decadal Survey missions to be developed and launched before the end of CY2017:

- SMAP (11/2014);
- ICESAT-2 (10/2015);
- CLARREO-1 (11/2017) as well as a CLARREO-2 (2020); and
- DESDynI Radar+Lidar (two spacecraft sharing a single EELV launch; 10/2017).

By launching these four missions within a three-year period, this acceleration allows NASA to achieve the scientific synergies intended by the NRC in defining the Tier 1 mission set. Both CLARREO and DESDynI will be designed to achieve focused science within realistic cost constraints (development and operations cost through FY2020: $600 million for the CLARREO-1 satellite; and for the combined DESDynI mission $1.1 billion for the Radar satellite and $580 million for the Lidar satellite).

Expanded Venture-class Program: The FY2011 budget request enables the expansion of the science-driven, competitive, Principal Investigator-led Venture-class program that was initiated in FY10 in two complementary directions:

- Release, beginning in late FY2011, of **annual** competitive Venture-Instrument solicitations, each for a single, $90M-class instrument (5-year development) for launch on a flight of opportunity; and,
- Release in FY2012 of the Venture-2 competitive solicitation for development and flight of a complete small mission ($150M NASA funding cap including launch vehicle; launch no later than FY2017 after a 5-year development). This continues the every-other-year pattern of solicitations alternating between aircraft and orbital opportunities that was initiated in the FY2010 program and advances the first small-sat call by four years from the FY2010 plan.

Climate Continuity Missions: The FY2011 budget request allows NASA to address important scientific needs for continuity of key climate observations.

- Refurbishment of the SAGE-III instrument and of a hexapod pointing platform, and accommodation studies for a flight opportunity on the ISS as early as 5/2014, if transportation to the ISS can be arranged;
- Development of a GRACE Follow-on mission (with a launch in 2016) as a gap-filler between the operating GRACE and the recommended higher-capability GRACE-II Decadal Survey Tier 3 mission.
- Development of an ocean color and clouds/aerosols polarimetry mission (launch in 2018) to bridge between existing on-orbit missions and the future, more capable ACE Tier 2 mission.

Accelerated Decadal Survey Tier 2 Missions: The FY2011 budget request enables the acceleration of the Decadal Survey's Tier 2 mission set, with two to be launched by the end of 2020 (ASCENDS (2019) and SWOT (2020)), and the others to be launched at the rate of approximately one each year beginning in 2021, compared with one every other year (and starting later) as enabled by the FY2010 budget. Based on scientific priorities, Administration objectives, technical maturity, and partnership opportunities, NASA will work with the USGCRP to determine the development order for the balance of Tier 2 missions.

Mission Infrastructure: Development of three new mission infrastructure projects that will enable more economical and scientifically efficient mission implementation: Dual Satellite System for economical use of Evolved Expendable Launch Vehicles; Standard Payload-to-Spacecraft Interfaces; and Upgraded Ground Systems for mission operations and data management.

2. Mission-enabling/Data-exploiting Research and Applications

The FY2011 budget request enables several key research, applications, technology, and education activities to be initiated or greatly expanded. These non-flight activities both enable the new space missions and provide the scientific and societal benefits from the spaceborne measurements.

- Modeling, assessment, and computing activities to expand NASA's contribution to the 2013 National Assessment by the USGCRP and the next mitigation and adaptation (Working Group II) assessment of the IPCC;
- Acceleration of operational use of NASA research data to improve climate prediction and weather forecasting, including expansion of SERVIR to additional nodes in strategic locations in the developing world in collaboration with USAID, and expansion of the sources and types of information products available to and from SERVIR nodes;
- Synthesis of NASA Earth Science observations via expanded opportunities for competitively-selected Interdisciplinary Science investigations and key mission science team work;
- Calibration of multi-satellite global data sets to enable increasing leverage of international data contributions, furthering the goals of USGEO and GEOSS;
- Development of NASA's contributions to a national Carbon Monitoring System in collaboration with other federal agencies;
- Expanded Earth Science Technology Program to provide the technology advances needed to enable accelerated implementation of Decadal Survey Tier 2 & 3 missions;
- Commensurate investment in Earth Science education programs such as GLOBE to assure that new Earth science understanding is infused in the nation's education curricula and that an educated workforce and populace is equipped to use the results of NASA's Earth Science program.

3. Assembling the Components to Meet National Needs

The broad range of space missions and research activities enabled by the budget request and described above have been chosen and sequenced to enable them to be combined to make essential contributions to key national needs:

- **Climate monitoring and research**—Addressing the causes and consequences of climate change requires diversity and continuity of data from satellite, in-situ and surface-based observing systems, along with associated research in key areas including atmospheric composition, Earth's gravity field, ocean color, and satellite data-driven climate modeling. The expanded flight components increase the breadth of simultaneous, high-quality spaceborne measurements that will be acquired by NASA as well as addressing threats to continuity for selected key data sets. Portions of the non-flight research and technology programs serve to allow multiple measurements, from different sources and missions, to be effectively synthesized into consistent, comprehensive data sets that can be extended into the future;
- **Carbon Cycle Research, Monitoring, and Product Generation**—Accurate understanding of carbon storage in and exchange among the atmosphere, ocean and biosphere is critical to projecting with confidence the future evolution of climate. Global measurements from space must be supplied to complement data from in-situ and surface measurement networks. The planned sequence of missions (OCO-2 in 2013, OCO-3 instrument ready for flight in 2015 and ASCENDS accelerated for launch in 2019) initiates a sustained, global, scientifically based, spaceborne system for atmospheric CO_2 and monitoring of natural sources and sinks. The expanded suite of pilot carbon measurement system projects—drawing through competitive solicitations from the research, engineering, agency, and private sector communities—will advance scientific

understanding, develop expertise and identify issues associated with the synthesis of disparate, technologically challenging carbon measurements to form useful monitoring products, and inform the design and architecture of the much-larger, interagency carbon monitoring system required by the nation;

- **Essential contributions to the USGCRP's 2013 U.S. National Assessment**—The community of researchers skilled in using NASA satellite data will be funded to conduct analyses and contribute products essential for the success of the assessment. This will ensure that the spaceborne measurements will be properly and fully utilized in the Assessment, and will strengthen the ties between the NASA research/applications development communities on the one hand, and the traditional user, policy-making, and stakeholder communities on the other hand;
- **Means to rapidly respond to results of research and to partnership opportunities**—The combination of expanded Venture class and innovative mission infrastructure will enable NASA to increase its engagement with both traditional and emerging space-faring domestic, international, and private-sector partners.

The result is a NASA Earth Science program sized and shaped to greatly enhance NASA's contributions to the space-based observations, research, and applications the nation requires in order to respond to the challenges of climate change.

Introduction

NASA pioneered the interdisciplinary field of Earth System Science—the study of the Earth as an integrated system. This approach to studying the Earth as a single complex system is essential to understanding the causes and consequences of climate change and other global environmental concerns. Spaceborne instruments provide essential broad coverage, high spatial resolution, frequent sampling, and near-uniform accuracy and stability. Multiple on-orbit missions, including those flying in coordinated orbits as part of planned constellations, allow data to be acquired simultaneously on many important quantities, enabling investigations of the interactions among the coupled Earth processes that constitute the climate system. Wide-ranging research and analysis (R&A) and Applied Sciences Programs involving nearly 1700 competitively selected research tasks advance science and understanding through analysis of NASA and non-NASA satellite measurements as well as data from airborne campaigns and ground-based instruments. This work, coupled with that of NASA's partners in the U.S. Global Change Research Program, provides much of the nation's knowledge base for understanding, mitigating, and adapting to climate change.

The first Earth Science Decadal Survey, conducted by the National Academy of Sciences and published in January 2007, noted with alarm the decline of NASA's Earth Science budget since 2000 and found that the nation's system of environmental satellites was "at risk of collapse". In addition, the Obama Administration, recognizing the pressing challenge of climate change, observed the need to address continuity of key climate measurements in order to inform policy and action.

With the 2009 American Recovery and Reinvestment Act and the Fiscal Year (FY) 2010 budget, the Administration and Congress placed on a firm path for completion the Foundational Missions that NASA had under development at the time the Decadal Survey was published and which were among the Survey's first recommendations. With the President's FY2011 Budget Request, the Administration has moved to accelerate substantially NASA's fulfillment of other key Decadal Survey recommendations as well as address related Administration climate change priorities.

The requested budget for NASA Earth Science, totaling $10.3 billion from FY11–15, is consistent with the recommendations of the Decadal Survey, which called for rapid restoration of NASA's Earth Science Division budget to the 2000-era level of ~$2B annually (in FY06 dollars). This funding level constitutes the largest increase of any of the Federal agencies contributing to the US Global Change Research Program (USGCRP). The budget request raises NASA's FY11 investment in the USGCRP by $214M, nearly 50% of the overall increase for USGCRP ($439M), and continues NASA's role as the largest federal agency contributor to the USGCRP—$1.285B (~50%) of the total of $2.561B from FY11–15.

Pursuant to the 2008 NASA Authorization Act (P.L.110-428) and Conference Report (House Report 111-366) accompanying the FY2010 Consolidated Appropriations Act (P.L.111-117), this report outlines the NASA Earth Science activities that will be pursued to maintain and improve our understanding of the Earth's climate. The focus of the report is the set of accelerations and expansions to the NASA Earth Science Program enabled by the FY2011 President's Budget Request. This plan describes an integrated program that is consistent with the comprehensive vision for NASA's Earth Science endeavor set forth in the NRC's Decadal Survey, as well as with the Administration's focus on climate research and monitoring to advance science, expand applications, and address national information requirements for near-term policy development and future evaluations of policy efficacy. The budget request thus allows for the acceleration and expansion of investigations and initiatives across the entire portfolio of coordinated Earth Science program activities—in the areas of flight mission development, research, applications development, and technology development.

The unique and essential strength of the NASA Earth Science program derives in large part from its deliberate investment balance between flight programs on the one hand, and research, applications, data systems, and technology activities on the other hand. Indeed, NASA is the only space agency in the world with an integral associated major science and applications research program; NASA is likewise the only science agency with broad engineering expertise and access to space. Preserving the balance and comprehensive scope of the Earth Science program was a key theme of the Decadal Survey; while the majority of government and community attention has been paid to the Survey's specific new flight mission recommendations (the 15 NASA Tier 1–3 missions and Venture-class), the Survey contained some 18 additional recommendations relevant to NASA activities in non-space-flight project areas. Similarly, the FY11 budget request addresses non-flight activities such as climate research and modeling, adaptation and applications activities, and education.

The following sections describe the work to be accomplished with this addition of budgetary resources, in the *component* categories of new and accelerated missions and innovations, mission-enabling/data exploiting activities, and the *integrative* category of assembly of components to meet national needs.

- Under *Space-based Observing Systems*, this plan identifies the space-based activities resulting from, or modified by, the budget request. These include a new mission to replace the Orbiting Carbon Observatory, the acceleration of all four Tier 1 Decadal Survey missions into a three-year window from 11/2014 to 11/2017, the acceleration and expansion of the Venture class program, the identification and development of a new set of missions to address continuity of key climate measurements, and the acceleration of Tier 2 Decadal Survey missions, including two of the Tier 2 missions to be developed for launch in this decade.

- Under *Mission-enabling and Data Exploiting Activities*, this plan describes how targeting a portion of the budget request allows these missions to be enhanced and their data employed effectively in research and modeling to generate scientific information products for national and international climate change assessments and other applications.

- Under *Assembling the Components to Meet National Needs*, this plan describes how the components in the previous two sections have been designed and sequenced so as to be combined in order to address key issues identified by the Administration: climate monitoring, the carbon cycle, the 2013 US National Assessment, and the ability of the Earth observation program to respond rapidly to new scientific understanding and partnership opportunities.

This document includes Appendices on Foundational Missions (A), Mission Cost Estimation (B) and Missions Observations and Societal Benefits (C).

2. Components of a Climate-centric Architecture for Earth System Science and Applications

The President's FY2011 Budget Request includes a substantial new investment in NASA's Earth Science program to advance the science of climate change and related environmental concerns arising from natural and human-induced changes in the Earth system. This budget request enables the expansion of the base NASA Earth Science program and acceleration of deployment of new satellite missions. These include those missions recommended by the NRC Decadal Survey and those required to improve continuity of selected key climate observations. These are overlapping sets, with climate science needs driving some choices in the acceleration of Decadal Survey missions.

2.1 Space-based Observing Systems

The FY2010 budget and the FY2009 American Recovery and Reinvestment Act funds placed the Foundational Missions (Appendix A) on firm footing, with appropriate budget and schedule reserves to enable their successful completion and deployment. These funds also enabled initial work on the new mission set recommended in the NRC Decadal Survey. The FY2010 budget funded the initiation of the first two Decadal Survey new mission recommendations, the Soil Moisture/Active and Passive (SMAP) and ICESat-2, and pre-formulation studies of additional missions.

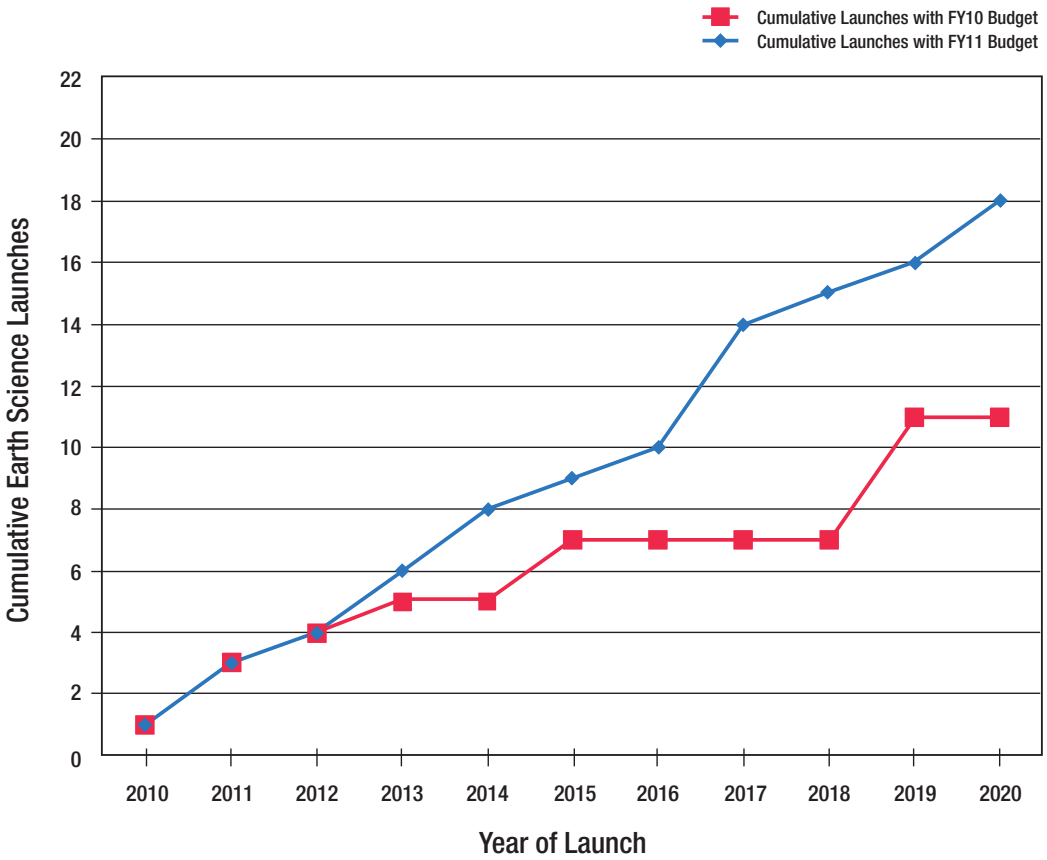


FIGURE 1: Comparison of Earth Science mission launches under the FY2010 budget (in RED) and the FY2011 budget (in BLUE).

The President's FY2011 budget request enables a broad, robust observation and analysis program to develop a better understanding of the global, integrated Earth system. For the space flight activities of the Earth Science program the augmented budget enables an acceleration of the launch readiness dates for SMAP, DESDynI, and CLARREO, and the significant acceleration of the broader Decadal Survey mission recommendations. Figure 1 shows the increase in the cumulative number of satellite mission launches enabled in this decade by this budget request. Figures 2 and 3 show the mission accelerations and new starts, respectively, enable by the FY2011 budget request.

In addition to the acceleration of the mission launch cadence, the budget request also enables an invigorated Venture class line of competitive selections to provide space flight-ready facility instruments. The more frequent launch schedule creates more opportunities for enhanced cooperative science from constellation flying, as significantly more missions will be launching and flying over the period from 2014 to 2020. The greater number of missions being developed and completed will also make possible co-manifested launches. With the budget NASA will fund the development of a fully qualified dual payload attachment feature enabling the more efficient use of the capacity of the nation's largest and most reliable launch vehicles, the Evolved Expendable Launch Vehicles (EELV). The imminent retirement of the Delta-II class of launch vehicles creates an urgent need for this capability.

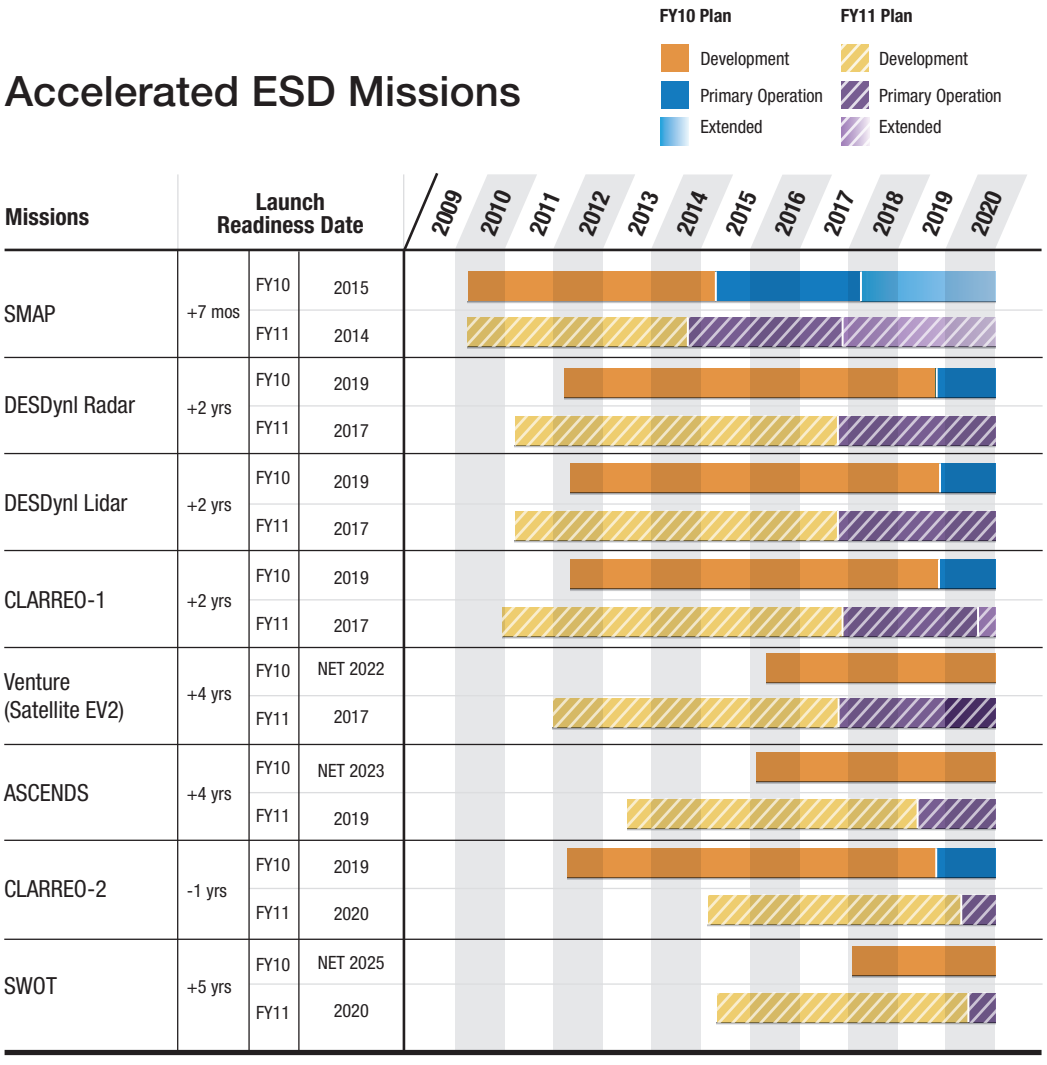


FIGURE 2: Accelerated Missions—This figure compares the timelines for mission development associated with the FY2010 and FY2011 budgets. The FY11 budget request substantially accelerates the development and launch of Decadal Survey-recommended missions.

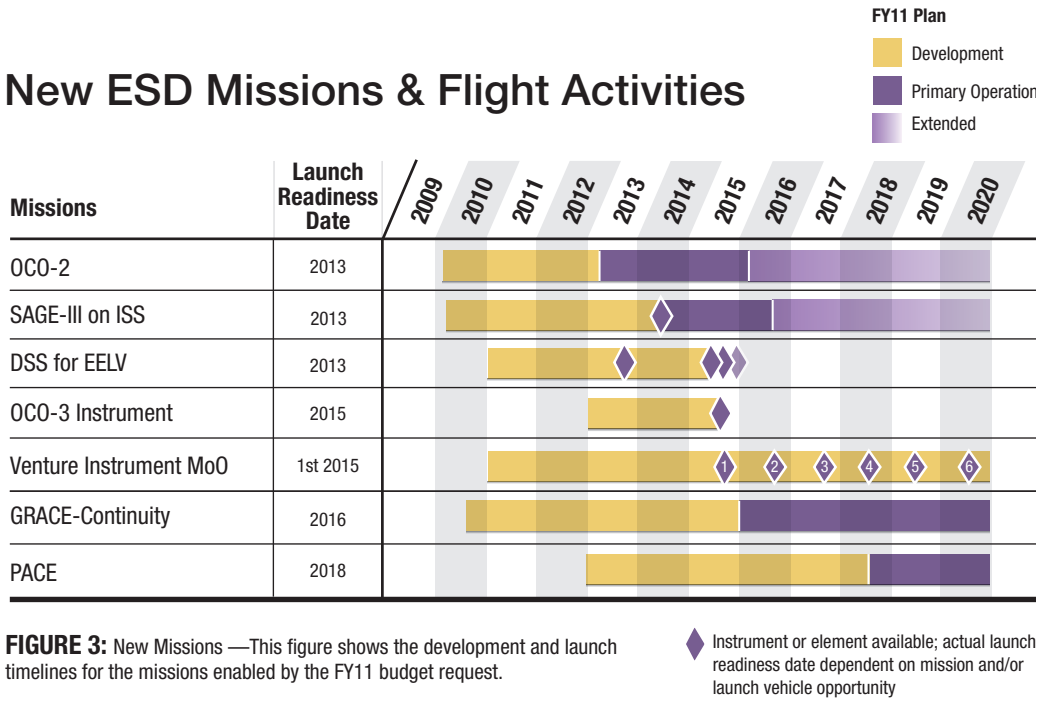
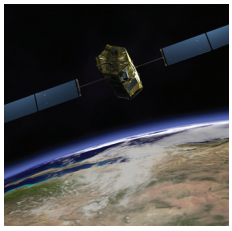


FIGURE 3: New Missions —This figure shows the development and launch timelines for the missions enabled by the FY11 budget request.

2.1.1 Orbiting Carbon Observatory-2, LRD 2013



The Orbiting Carbon Observatory 2 (OCO-2) will provide the global measurements of atmospheric carbon dioxide, CO_2 that were planned for the OCO mission, and much anticipated by both the scientific and policy communities. The President's FY2011 budget request funds the development of OCO-2 for launch in early CY 2013.

OCO-2 will make precise, time-dependent, global measurements of atmospheric CO_2 mixing ratios over the sunlit hemisphere of the Earth, using a spaceborne instrument. These measurements will be combined with data from a ground-based network to provide scientists with the information needed to better understand the processes that regulate atmospheric CO_2 and its role in the carbon cycle. This enhanced understanding is essential to improving predictions of future atmospheric CO_2 increases and the potential impact on the climate. The understanding and information products will aid policy makers and business leaders in their decision processes.

OCO-2 is based on the original OCO mission that was developed under the NASA Earth System Science Pathfinder (ESSP) Program, only to be lost due to a launch vehicle failure on February 24, 2009. Following the loss of OCO, NASA initiated science activities to refine OCO retrieval algorithms and validation approaches by analyzing data collected by JAXA's GOSAT atmospheric carbon dioxide measuring mission. Additionally, with a view toward reducing the risk associated with an OCO replacement mission, NASA authorized targeted procurements of significant, obsolete spacecraft/instrument parts and key long-lead components.

On March 8, 2010 NASA approved, in a senior management Acquisition Strategy Meeting, a Tailored Formulation Period (TFP) authorizing the Earth Science Division and the OCO-2 mission to move forward. NASA is utilizing $50M in funds directed by the FY2010 Congressional appropriation for the mission. NASA will complete mission formulation activities for the OCO-2 mission during FY2010 and will move into full mission development at the start of FY2011. The project will plan for an estimated 28-month mission implementation, following Authorization

Polar Ice

The FY2011 budget request will significantly enhance NASA's ability to observe the distribution of ice in the polar regions, to use the observations for quantitative research, and to inform models and assessments with the observed data.

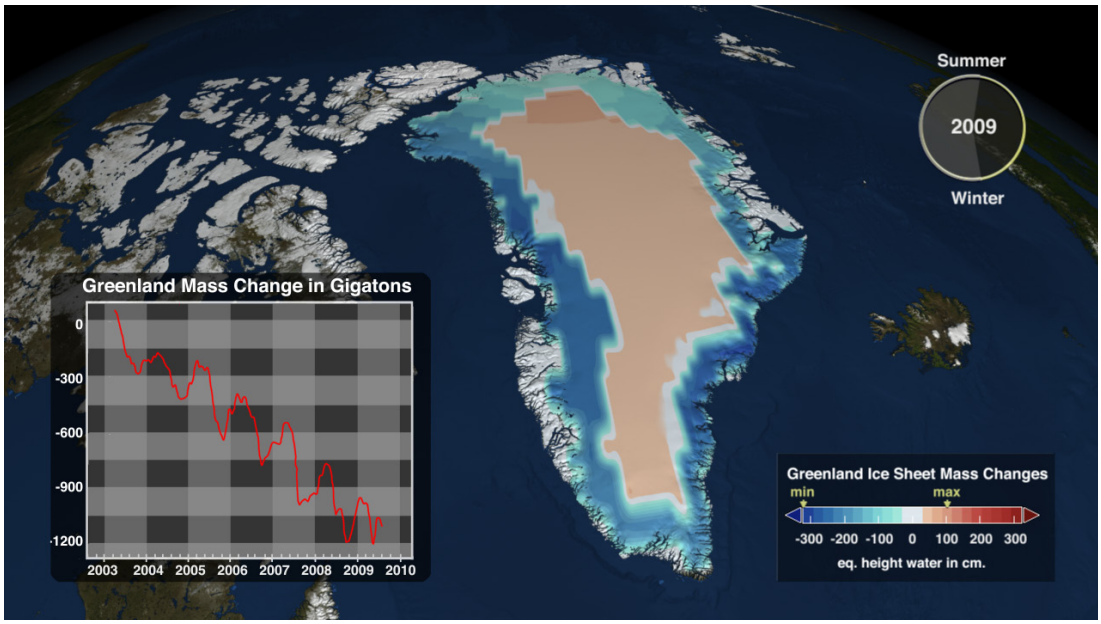


Image: This image shows the change in mass of the Greenland Ice Sheet over the period April 2003–July 2009 as measured by GRACE. Credit: NASA Goddard Space Flight Center/Science Visualization Studio. Blue Marble data is courtesy of Reto Stockli: NASA/GFSC

- **Monitoring ice sheet and sea ice thickness and stability**—The ICESat II mission (planned launch in 2015) will extend and expand upon the measurements made by the ICESat mission (2003–2009) of ice sheet and sea ice thickness made in both the Arctic and Antarctic. The DESDynI lidar will provide seasonal measurements of the changes in thickness of ice sheets, glaciers, and sea ice. The DESDynI radar will track the velocities ice flowing to sea within outlet glaciers- as well as monitor the grounding line of those glaciers—both measurements of ice sheet stability.
- **Monitoring of ice sheet mass**—The GRACE FO mission (planned launch in 2016) will extend (and improve upon) the measurements of ice sheet mass made by the GRACE mission (launched in March, 2002).
- **Monitoring of sea ice extent and motion**—The Japanese AMSR-E instrument aboard NASA's Aqua mission, launched in 2002, provides continuing coverage of the spatial extent of sea ice at high latitudes. The DESDynI radar will provide nearly continuous measurement of all sea ice movement in Arctic and Antarctic seas.
- **ICEBridge series of aircraft missions**—The ICEBridge series of focused airborne field campaigns, begun in 2009, will utilize airborne radars and lidars to obtain information on ice sheet and sea ice thickness to help provide continuing information on evolution of ice sheet and sea ice thickness in the interval between the ICESat missions. The budget request provides targeted funds for a focused, competitive community-based research program utilizing ICEBridge data.
- **Dynamical ice modeling and its incorporation into global climate models**—NASA's satellite missions provide important data sets for initialization and evaluation of NASA's climate models. The budget request will allow for enhanced investments in the observationally-driven (using data from ICESat II, GRACE FO, and DESDynI) representation of ice sheets and sea ice in NASA climate models and in the application of these models to support national and international assessments, enabling improved simulation of future sea level rise and its impacts.

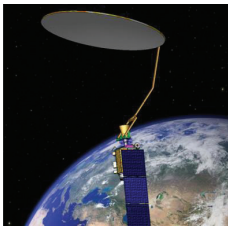
to Proceed, for an early 2013 launch. To ensure this earliest launch of the OCO-2 mission, NASA will procure a complete set of instrument spare parts. These parts will not be assembled into a completed instrument by the OCO-2 project, but their availability will ensure a full set of flight spares as risk mitigation for the OCO-2 mission.

Following a successful OCO-2 development and launch, it is NASA's plan to develop and assemble a complete stand-alone OCO-3 instrument from the remaining OCO-2 flight spares, to be available as an instrument for a flight of opportunity as early as 2015. The budget for this activity includes appropriate instrument accommodation costs (such as specialized secondary pointing mechanisms). The OCO-3 instrument may fly as NASA's contribution to a future partner mission or as an instrument on another NASA mission. It could also serve as a key, complementary element of the Earth Science Decadal Survey CO_2 mission Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS), now planned to fly in 2019.

2.1.2 Tier 1 Mission Accelerations

The President's FY2011 budget request allows all four Decadal Survey Tier 1 missions to be developed for launch in a three-year period, from 11/2014 to 11/2017, matching the Decadal Survey schedule (albeit four years later than hoped for by the NRC panel). This launch sequence will permit simultaneous operation of these missions for several years, achieving the synergy among measurements intended by the Decadal Survey. Further, once on orbit this set of missions will substantially advance water cycle science, with GPM, SMAP, ICESat-2, DESDynI, and perhaps Aquarius in extended mission phase all simultaneously observing various phases of the water cycle. The resulting set of measurements will present a substantial capability for observing climate change impacts, and provide information important to mitigation and adaptation decisions.

Soil Moisture, Active and Passive (SMAP), LRD 2014



The Soil Moisture Active and Passive (SMAP) mission will provide new information on global soil moisture and its freeze/thaw states enabling new advances in water cycle and climate science and short-term forecasting. The President's FY2011 budget request enables NASA to accelerate the planned activities for the SMAP mission, moving its target launch forward seven months to November 2014. Based on present programmatic knowledge, the 11/2014 date represents the earliest launch date for the mission and is dictated by technical, rather than budgetary, constraints.

Direct measurements of soil moisture and freeze/thaw states are needed to improve our understanding of regional and global water cycles, terrestrial ecosystems, and the processes that link the water, energy, and carbon cycles. Soil moisture and freeze/thaw information provided by SMAP will lead to improved weather forecasts, flood and drought forecasts, and predictions of agricultural productivity and climate change, as well as to improved understanding of the sources and sinks of carbon. SMAP will contribute to the goals of the Carbon Cycle and Ecosystems, Weather, and Climate Variability and Change Earth Science focus areas as well as to hydrological science.

In FY2010 SMAP completed mission concept development and entered into formal mission formulation. The previous launch readiness date was funding-constrained. The FY2011 budget request allows the earliest possible launch readiness date consistent with technical constraints (principally launch vehicle acquisition and instrument development). The accelerated launch enabled by the President's FY2011 budget request not only will deliver the measurements earlier, but may also lead to a reduced overall mission cost through a more efficient mission development funding profile. Furthermore, through budget-enabled enhancements to the Applied Science and Research programs, NASA will ensure a rapid and more efficient utilization of the SMAP data by the operational user community than was previously deemed possible.

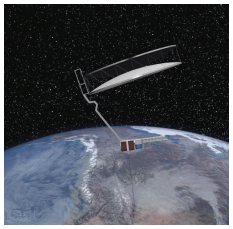
ICESat-2 (LRD 2015) and IceBridge

The ICESat-2 satellite and the IceBridge airborne campaigns will continue and expand upon the measurements begun with the (2003–2009) ICESat mission, measuring elements of ice-sheet mass balance and land-surface topography to quantify polar ice sheet contributions to sea level changes and the linkages to climate. The President's FY2011 budget request enables the expansion of the IceBridge activities to cover the necessary measurements bridging the observation gap between the end of the ICESat mission in 2009 and the launch of ICESat-2 in 2015.

ICESat-2 data will improve predictive models by quantifying regional signatures of ice sheet changes to assess mechanisms driving those changes. Enhancements to the ICESat-2 mission over the original ICESat will allow more accurate and frequent measurements of the ice slopes, enabling accurate, rapid seasonal assessments of ice sheet variability. The science focus areas served by ICESat-2 include Climate Variability and Change, Earth Surface and Interior, and Global Water and Energy Cycle.

The FY2010 budget allows the earliest possible launch readiness date for ICESat-2 consistent with technical constraints (again, principally launch vehicle acquisition and instrument development). The President's FY2011 budget request will support the full funding and capability of the IceBridge data continuity airborne science campaign. This sustained, multi-year series of flights will help to bridge the data gap between the end of the ICESat mission (December 2009) and the launch of ICESat-2 in 2015. The IceBridge effort will also provide opportunities for ICESat-2 pre-launch calibration and algorithm validation.

Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI), LRD 2017



The Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission will advance understanding of key impacts of climate change, especially sea level rise and changes to the Arctic sea ice cover, the effects of changing climate and land use on terrestrial carbon storage, fluxes of carbon dioxide to the atmosphere, and species habitats. The President's FY2011 budget request will enable the design and development of a scientifically viable, cost-constrained mission that can launch in 2017, as compared with previous budget-constrained launch dates that were no earlier than 2019.

DESDynI will obtain radar and lidar measurements to study change occurring in the polar ice sheets, characterize global vegetation three-dimensional structure, and advance solid Earth science through quantifying surface deformation. It will advance our knowledge and understanding of critical Earth science questions pertaining to natural hazards, especially earthquakes, volcanic eruptions, and landslides in addition to impacts of climate change. DESDynI will also provide significant, new observational resources for other applications, including monitoring subsurface fluid flow and carbon sequestration sites, monitoring the health of forests and other agricultural resources, providing support for natural disaster recovery and response efforts, and monitoring all major mountain glaciers.

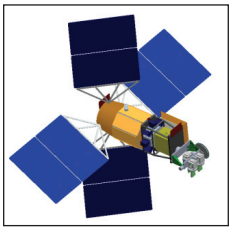
DESDynI's radar and lidar are used together in "fusion" algorithms that combine the high spatial and temporal resolution of radar with the superior vertical structure and accuracy of the sparser lidar data to produce maps of vegetation structure, biomass, disturbance and recovery. The DESDynI mission provides measurements of the quantity of aboveground carbon and its changes at sufficient resolution—a few hectares—to be of value to individual, traditional, *in-situ* projects and to enable inter-comparisons with other high-resolution satellite observations. DESDynI will initiate measurements providing a stable and consistent framework from which domestic and global estimates of forest carbon and its changes can be monitored from local to national scales.

In FY2010 NASA will complete all necessary mission definition activities, allowing DESDynI to move into formulation in FY2011. Included in the initial studies have been detailed mission partnership discussions with the German Aerospace Center (DLR). The DESDynI mission consists of two separate but coordinated satellites, with planned substantial on-orbit overlap. One satellite will host an L-band Synthetic Aperture Radar (SAR) operated as a repeat pass interferometer (InSAR) and the second satellite will include a multi-beam profiling lidar. With the development of the Dual Satellite System (DSS) capability for the Evolved Expendable Launch Vehicles (EELV) made possible by the budget request and the increase in available resources, the baseline plan calls for the two satellites to be co-manifested on a single EELV. However, the final launch configuration will be defined in FY2012, prior to the mission confirmation and launch vehicle selection.

Mission development progress on DESDynI had been limited by available funds in the FY2011–FY2013 period. However the President's FY2011 budget request allows DESDynI to move more rapidly into development, accelerating the target launch date by two years, to FY2017. The DESDynI mission included in this plan shall be implemented within a defined cost constraint that supports the development of a scientifically viable DESDynI mission launching 2017 as one important element of a robust, integrated Earth Science program. Leading up to the start of the DESDynI mission in early FY2011 NASA will complete a comprehensive review of the integrated science performance requirements and the required engineering implementation to deliver the essential DESDynI mission objectives. As NASA defines the DESDynI mission it will evaluate program options that meet the primary DESDynI unique science objectives while maintaining the balance and integrity of the overall Earth system science objectives. The options under consideration include but are not limited to: (1) delay (either minor or major) in the completion of other important program elements to accomplish DESDynI objectives, (2) split development of the DESDynI radar and lidar satellites while possibly leveraging overlap with other relevant lidar measurements for the required fusion data products, and (3) different DESDynI mission implementation approaches including selecting the mission implementation through a full and open competition solicited through an Announcement of Opportunity (AO).

NASA is committed to exploring all necessary options to define the appropriate DESDynI mission as it transition into formulation and development in early FY2011.

Climate Absolute Radiance and Refractivity Observatory (CLARREO), LRD 2017 and 2020



The Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission will provide critical new climate observations by measuring the spectrally resolved components of the reflected solar radiation and the Earth's outgoing thermal radiation. CLARREO will also provide an absolute reference standard to improve the accuracy of other orbiting measurements and to provide rapid, accurate estimates of decadal-scale climate trends. With the President's FY2011 budget request NASA will accelerate the development of a scientifically viable, cost constrained mission with the first launch in 2017, and the second in 2020.

The CLARREO mission is designed to monitor and understand changes in the climate system, and many of the important feedback mechanisms, in unique ways that ensure well-validated traceability to absolute SI-calibrated physical standards. Such precision is necessary to determine small changes in climate-signal strengths while piecing together observations made over decades with no guarantee of overlap, and to account for individual instrument signal drift. The approach for the NASA portion of CLARREO is to obtain spectrally resolved radiances throughout the entire thermal infrared wavelength region and reflected solar from the near infrared to the ultraviolet. Spectrally resolved radiances are needed to fully separate and identify changes in the terrestrial radiation budget from the various feedback mechanisms (for example, the water vapor feedback, cloud feedback, etc.) that are predicted to change as the climate system evolves, yet still have significant uncertainties in models. Each set of data will be collected with instruments optimized to reduce drift and ensure connections to physical standards. CLARREO will also include GPS radio occultation (GPS-RO) measurements to provide a second, and unique, set of observations on changes in the atmospheric temperature and water vapor profile in a way that is traceable to units of time.

Mission development progress on CLARREO had been limited to date by funds available in the FY2011–FY2013 period. However, the President's FY2011 budget request allows CLARREO to move more rapidly into development. NASA has completed a series of mission implementation option analyses, and these studies have indicated that the CLARREO objectives can be met with two satellites launched no more than three years apart. The two-step mission approach will ensure a long time period where CLARREO observations could provide inter-sensor calibration with the operational sounding satellites from NASA, operational weather satellites, and space agencies from other nations. With the longer operating period, CLARREO will also provide improved sampling of the inter-annual variability of the climate signal, particularly providing better observation of a full El Niño/La Niña cycle, which can take up to seven years. With the President's FY2011 budget request, NASA will accelerate the CLARREO-1 launch from FY2019 to FY2017, and will launch CLARREO-2 in FY2020.

The CLARREO mission included in this plan shall be implemented within a defined cost constraint that supports the development of a scientifically viable CLARREO mission with an initial launch in 2017 as one important element of a robust, integrated Earth Science program. Leading up to the start of the CLARREO mission in early FY2011 NASA will complete a comprehensive review of the integrated science performance requirements and the required engineering implementation to deliver the essential CLARREO mission objectives. As NASA refines the CLARREO mission it will evaluate program options that meet the primary CLARREO unique science objectives while maintaining the balance and integrity of the overall Earth system science objectives. The options under consideration include but are not limited to: (1) delay (either minor or major) in the completion of other important program elements to accomplish CLARREO objectives, (2) a phased capability for the two satellites, with increasing performance for the second, and (3) different CLARREO mission implementation approaches including selecting the mission implementation through a full and open competition solicited through an Announcement of Opportunity (AO).

NASA is committed to exploring all necessary options to define the appropriate CLARREO mission as it transitions into formulation and development in early FY2011.

2.1.3 Venture Class Expansion

The President's FY2011 budget request enables NASA to institute a well-balanced Venture class program consisting of: (1) solicitations for sustained sub-orbital or airborne science campaigns; (2) solicitations for small satellite, complete mission proposals; and (3) annual solicitations for spaceflight-ready orbital instrument development. The third element of this triad is new and enabled by the President's FY2011 budget request.

On a par with their satellite mission recommendations, the NRC Decadal Survey recommended creation of a Venture class program of small, frequent, regular (predictably scheduled) science mission opportunities to spur innovation and enable the training of future Earth science leaders. The Venture class adds a necessary element of flexibility and robustness to what would otherwise be a fully subscribed strategic program. In addition to developing future PI researchers and supporting space flight instrument development, the Venture class competitions will prepare a selection of flight ready instruments that can be flown on future Earth science research and Decadal Survey satellites and that are available to respond quickly to international partnership opportunities and new scientific findings.

Venture Sub-Orbital Solicitations, started in FY2009: In 2009 NASA released the Earth Venture-1 (EV-1) call for extended Airborne Science aerial observing campaigns. Selection of five Earth Venture airborne investigations were announced on May 27, 2010, with campaigns to run from 2011 through 2015. NASA plans to release the second sub-orbital call in FY2013, with science campaigns to run from 2016 through 2020.

Venture Small Mission Solicitation, starting in FY2012: NASA will release the first call for a complete space flight mission, EV-2, in FY2011 with the selection to be made in FY2012. The allowable science scope for mission

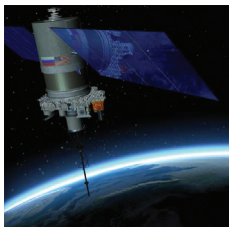
candidates will be coordinated with the Administration through the USGCRP; for the first solicitation for complete missions under the challenging cost and schedule constraints, it is likely that the call will be open to all compelling science investigations. This call is intended to solicit a stand-alone orbiting mission, with a cost cap of $150 million and a launch date no later than 2017.

Venture Instrument Solicitations—Annual starting in FY2011: With the funding in the President's FY2011 budget request, NASA's Earth Science program will further enhance the current Venture-class competitions with yearly Announcements of Opportunity to solicit proposals to develop flight-ready instruments. The overall objectives for these Missions of Opportunity investigations will be required to be relevant to the science priorities, goals, and objectives of NASA's Earth Science Program. The adoption of common instrument-to-spacecraft interface standards—developed as part of the overall budget request and discussed at the end of this section—will facilitate the flight of these instruments on a variety of partnership opportunities and available capacity on planned missions.

2.1.4 Climate Continuity Missions

The Administration recognizes the need for continuity in critical climate observations and data records. This plan provides for the development and launch of selected, high-priority climate data continuity measurements whose importance has become clearer since the release of the 2007 Earth Science Decadal Survey. The first of these is the replacement mission for the lost Orbiting Climate Observatory (OCO). Also included is the flight of the Stratospheric Aerosol and Gas Experiment (SAGE III) on the International Space Station and a follow-on mission to NASA's successful Gravity Recovery and Climate Experiment (GRACE) to serve as a bridge between the GRACE mission and the much more capable GRACE II Decadal Survey mission. These were chosen considering first scientific priority, then collectively cost, programmatic readiness and partnership opportunity.

Stratospheric Aerosol and Gas Experiment (SAGE III), LRD 2014



The Stratospheric Aerosol and Gas Experiment (SAGE III) will continue critical long-term measurements of the vertical structure of aerosols, ozone, water vapor, and other important trace gases in the upper troposphere and stratosphere. The President's FY2011 budget request provides for the refurbishment of an existing SAGE-III instrument, making it flight ready for observations as an International Space Station (ISS) external attached payload as early as late 2014.

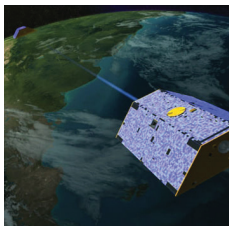
The SAGE series of instruments rely on the proven solar occultation technique and a mature, extensively validated algorithm. Each SAGE measurement is precisely radiometrically calibrated using solar data taken outside of the atmosphere; hence the data products and trends therein are to the first order insulated from long-term calibration variation and data gaps. SAGE III and its predecessor SAGE–series instruments have provided crucial data necessary for the international science community to study ozone and aerosol trends, climate change, and atmospheric chemistry and they remain the primary basis for the measurement of trends in ozone vertical profile and long-term variability in aerosols. Analysis of SAGE data documents the onset of recovery in stratospheric ozone.

This SAGE III instrument was originally manifested on the International Space Station (ISS) primarily because the ISS mid-inclined orbit of 51.6° allows excellent solar occultation measurement coverage providing near global coverage on a monthly basis (similar to the 57 degree inclination of SAGE II on ERBS). Planned as an Express pallet experiment, a SAGE III flight on the ISS today will require the development of a new SAGE III experiment pallet, and possibly additional accommodation changes to be defined. The SAGE III experiment pallet will in-

clude the existing SAGE III flight instrument and the existing European Space Agency (ESA)-developed Hexapod pointing platform.

The remaining SAGE III spaceflight instrument had been in storage since 2003. In FY2009 NASA removed the instrument from storage and thoroughly evaluated its condition. The instrument was found to be in excellent condition and ready for refurbishment and recertification for flight. The President's FY2011 budget request provides the necessary additional funds to refurbish the SAGE III instrument and operate it on the ISS for its life. In FY2011 NASA will initiate the instrument refurbishment and the engineering studies to host the payload on the ISS. An integrated engineering analysis of the SAGE III experiment pallet will be performed to ensure compatibility with the ISS launch and operational environment and full environmental testing will be performed to verify end-to-end system performance prior to launch. NASA's Science Mission Directorate and Space Operations Mission Directorate have had initial discussions on the accommodation of SAGE III on ISS and will work together on a collaborative arrangement to transport SAGE III to ISS and install and operate it as an external attached payload.

Gravity Recovery and Climate Experiment Follow-On (GRACE FO), LRD 2016



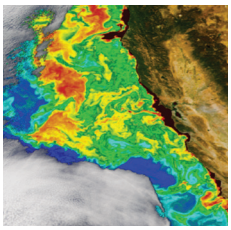
The Gravity Recovery and Climate Experiment (GRACE) mission's precision measurements of the Earth's gravitational field have revealed with steadily increasing accuracy the patterns of movement of underground water reservoirs and their seasonal variability. The President's FY2011 budget request will enable the development and launch of a GRACE follow-on mission to continue these important climate measurements until the more capable Decadal Survey GRACE-II mission can be developed.

The GRACE two-satellite mission launched in March 2002 has enabled the measurement of the Earth's gravitational field with a precision of an order of magnitude higher than ever before. This precision has in turn enabled the measurement of the time variable gravity field, which is due to the planet's mass re-distribution. These measurements constitute the first-ever monthly determinations of the Earth's gravitation. These monthly data, in combination with several other data have led to great discoveries in understanding the Earth system, surpassing the expectations of its developers, and hold significant keys to climate change research and future climate adaptation.

Within a few years of the GRACE mission, scientists were able to discern underground water patterns and their seasonal variability. Recently, as the GRACE data record is reaching eight years, studies of underground water resources have indicated trends. Most notably, a recent study showed that the aquifers for California's primary agricultural region—the Central Valley—and its major mountain water source—the Sierra Nevada mountain range—have together lost nearly enough water to fill Lake Mead, America's largest reservoir. This reflects California's extended drought and increased rates of groundwater being pumped for human uses, such as irrigation. This trend will potentially lead to declining water tables, water shortages, decreasing crop sizes and continued land subsidence. Such findings have major implications for California's agricultural production and exports, and therefore, the U.S. economy. Continuing GRACE type measurements will provide the US and global communities with a unique tool for managing one of the most critical issues in climate adaptation, water resources.

The President's FY2011 budget request will allow NASA to initiate a GRACE follow-on (GRACE FO) mission in partnership with the German Aerospace Center (DLR), consisting of two spacecraft flying in tandem. The GRACE FO mission will have two identical spacecraft flying about 220 kilometers apart in a polar orbit 500 kilometers above the Earth. In order to continue the science data from the GRACE mission, the GRACE FO data will consist of the inter-satellite range change measurements, the accelerometer, GPS and attitude measurements from each satellite. GRACE FO will undergo a Phase A mission concept development through FY2011, followed by development for launch readiness in approximately FY2016.

Pre-Aerosol, Clouds, and Ocean Ecosystem (PACE), LRD 2018



The Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) mission will make essential global ocean color measurements, essential for understanding the carbon cycle and how it both affects and is affected by climate change, along with polarimetry measurements to provide extended data records on clouds and aerosols. The President's FY2011 budget request enables the development for launch in 2018 of this critical measurement.

The PACE mission will extend key climate data records whose future was in jeopardy prior to the FY2011 budget request. Global ocean color measurements, essential for understanding the carbon cycle and how it affects and is affected by climate change, will be made by a radiometer instrument on this mission. A polarimeter instrument will extend data records on aerosols and clouds using this approach begun by the French PARASOL mission and expanded upon by NASA's planned Glory mission, as well as multi-spectral and multi-angle measurements made by NASA's MODIS and MISR instruments on NASA's EOS platforms (MODIS on Terra and Aqua, MISR on Aqua).

The Intergovernmental Panel on Climate Change (2007) identified the largest uncertainty in our understanding of physical climate as that due to aerosols and clouds. New and continuing global observations of ocean ecology, biology, and chemistry are required to quantify aquatic carbon storage and ecosystem function in response to human activities and natural events. A key goal is improvement of climate-carbon and climate-ecology model prediction. The blend of atmospheric and oceanic requirements is critical as ocean biology is affected by deposition of aerosols onto the ocean, which in turn, produce aerosol precursors that influence climate.

The PACE mission will serve to make these measurements until the readiness of the more advanced Aerosols-Clouds-Ecosystems (ACE) mission recommended by the NRC Decadal Survey for its Tier 2 mission set. The ACE mission will reduce uncertainties in major climate forcings to enable better climate prediction, reduce uncertain-

International Collaboration

International collaboration is a hallmark of NASA's Earth Science program. The present constellation of operating research satellites is heavily international, with two-thirds including major contributions from other countries' space agencies. Indeed, the Earth Observing System was conceived as an international venture, and was founded upon principles of open data policies that the rest of the world, through the Committee on Earth Observation Satellites and the Group on Earth Observations, is stretching to adopt. NASA has expanded its international collaborative activities beyond the space-faring nations through suborbital and ground-based observing programs and participation in international research programs.

The Foundational Missions continue this pattern of international collaboration, with Argentina partnering with NASA on Aquarius, and Japan and NASA collaborating on GPM as they did with TRMM. The French space agency CNES continues its partnership with NASA on ocean radar altimetry via OSTM/Jason-2, and now that partnership is expanding to include EUMETSAT and NOAA which now operate Jason-2 and will take the lead on development of Jason-3 as an operational system.

NASA is actively engaged with foreign space agencies in planning future space missions. The President of the European Space Agency has recently expressed intent for greater collaboration with NASA. NASA and Japan are already collaborating on a scientific level on CO_2 observations based on Japan's GOSAT and NASA's plans for OCO-2. NASA is in discussion with the French and German space agencies on roles they might play in SWOT and GRACE-FO, repectively.

Climate change is a global challenge, and effective Earth observation, research, and applications development requires the participation of nations and research organizations around the globe. NASA's leading contributions are acknowledged and welcomed everywhere we go.

ties in ocean carbon cycling and biological processes to enable carbon monitoring and management, contribute to better weather forecasting, and delineate the impacts of weather events on coastal ecosystems to enable resource management. When flown, ACE's advanced atmospheric and oceanic observations will feed climate, carbon, and ecological models, enabling adaptation strategies as Earth's climate varies and changes. PACE will enable early returns in these science and applications arenas.

PACE will be an international partnership, with the polarimeter provided by Centre National d'Études Spatiales (CNES) to measure aerosol and cloud properties. Launching in 2014 or 2015, the capable European Space Agency (ESA) mission EarthCARE, addresses similar science focus areas as PACE, but lacks a polarimeter or an ocean ecosystem radiometer. As planned, the PACE mission will overlap with EarthCARE enhancing the value of both missions and enabling science not possible with either individual mission. The President's FY2011 budget request provides for the development of the PACE mission to start in FY2011, supporting mission launch in 2018.

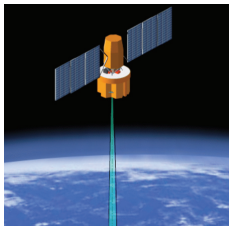
2.1.5 Tier 2 Mission Accelerations

The President's FY2011 budget request, provides sufficiently significant funding to permit planning for all, and implementation for some, of the Tier 2 Decadal Survey missions. NASA has evaluated a variety of factors in determining the first Tier 2 missions to proceed with next into development. These factors include, but are not limited to the following:

- Progress made in instrument development through the technology program, the Venture Class instrument solicitations, and the directed Decadal Survey mission studies;
- Actual operating lifetimes of the suite of NASA's and our international partners' Earth Observing satellites;
- Developments in our partners' mission and instrument programs;
- Developments in NASA's integrated Earth Science research activities, which may refine science priorities influencing the choice among mission options.

With the funds provided by the President's FY2011 budget request NASA will advance the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) and Surface Water Ocean Topography (SWOT) first, and other critical Tier 2 missions following at approximately one year intervals. Advance work on all Tier 2 and Tier 3 missions has been underway since FY2009. NASA's investments have included broad and extensive technology investments through the Earth Science Technology Office (ESTO), as well as well-focused mission studies. These activities will continue throughout the FY2011–FY2015 period as NASA completes the four Tier 1 missions. The mission sequence for the launches to follow SWOT in 2020 will be determined during this period (prior to 2015) as these technology investments and mission studies mature.

Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS), LRD 2019



The Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS), mission is the next step in precision monitoring of total column CO_2 in the atmosphere, extending the OCO-2 measurements through an active approach. The measurements from the active ASCENDS instruments would continue and complement the OCO-2 measurements. The President's FY2011 budget request will enable the start-up of the ASCENDS mission in 2013, with a target launch in 2019.

The ASCENDS mission was recommended by the NRC's Earth Science Decadal Survey as the next technological advancement of CO_2 observations from space after the operation of the Orbiting Carbon Observatory (OCO). Both OCO and ASCENDS are designed to sample the total column abundance of CO_2 around the planet with precision and accuracy sufficient to improve our understanding of the sources and sinks of atmospheric CO_2.

Water Availability and Quality

The FY2011 budget request will significantly enhance NASA's ability to observe the Earth's global water cycle, to use the observations for quantitative research, and to inform models and assessments with the observed data.

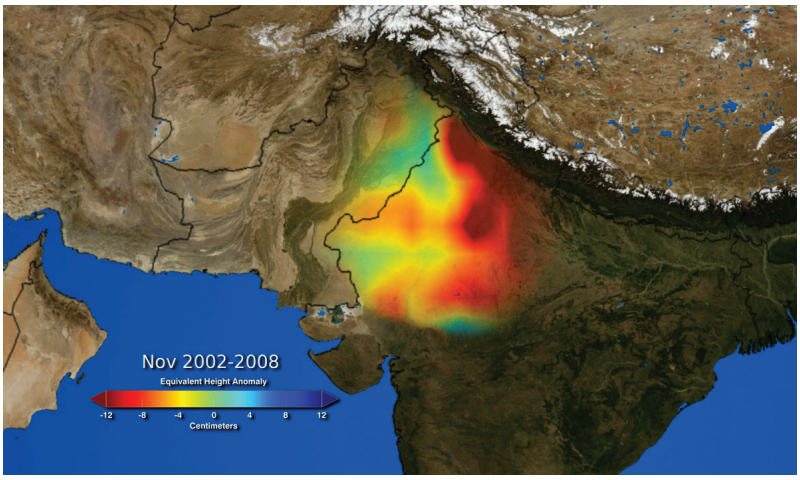


Image: Ground water depletion in the aquifer under Northern India totaled 109 cubit Km over the period of 2002–2008 as measured by GRACE. Credit: NASA Goddard Space Flight Center/Science Visualization Studio.

- **Precipitation**—The Global Precipitation Mission (GPM) to be launched in 2013 will provide an important advance over the currently operating (1997–present) Tropical Rainfall Measuring Mission (TRMM) by virtue of its higher latitude providing significantly enhanced geographical coverage, dual frequency radar providing information on precipitation type, and 3-hour temporal resolution of precipitation coming from its constellation of satellites using passive microwave sensors. While GPM itself is unchanged by the budget request, the opportunity for simultaneous operations with the FY11 accelerated and new missions will yield substantial scientific benefit.

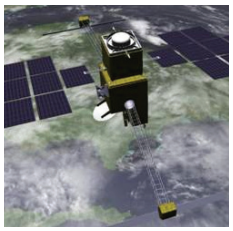
- **Soil Moisture and Freeze-Thaw State**—The launch of the Soil Moisture Active Passive (SMAP) mission, which will provide global measurements of soil moisture and freeze-thaw state, will be accelerated from 2015 to 2014 as a result of the budget request.
- **Inland Water (Lake, River) Height**—The launch of the Surface Water and Ocean Topography (SWOT) mission, now planned for launch in 2020, will provide unprecedented insight into the quantity of water in rivers and lakes (along with its higher resolution information on ocean surface topography).
- **Ground Water Measurements**—The GRACE FO measurements will provide information on changes in ground water stored in underground aquifers, building upon the approach demonstrated with the GRACE mission.
- **Glacier Volume Changes**—the ICESat-2 and DESDynI lidars can provide information about glacier volumes and their changes over time, especially, but not exclusively, at high latitudes.
- **Water Quality in Coastal Regions**—The launch of the Ocean Ecosystem Spectroradiometer (OES) instrument aboard the first platform of the PACE mission, now planned for launch in 2018, will provide new, high quality information on the biogeochemical properties of coastal waters and their implications for ecosystem and human health.
- **Northern Latitude Land, Lakes, and Permafrost**—Change in these Arctic features is a bellwether of climate change more broadly, with substantial potential climate feedback effects due to the release of methane currently trapped in permafrost. Coupling of data from SMAP, SWOT, DESDynI, and GRACE FO will enable an integrated view of the land portion of the water cycle in this key region.
- **Accelerated operational use of NASA satellite data**—The budget supports enhanced funding of programs targeted towards accelerating operational use of NASA satellite data and associated state-of-the-art modeling, especially through programs carried out jointly with NASA's national and international partners. This represents activities of NASA's Research and Applied Sciences Programs, and includes a significant increased investment in the SERVIR activity, which is crucial in providing near real-time decision support for foreign governments in times of floods and droughts.
- **Enhanced modeling and assimilation of the global water cycle and support for assessments**—The budget provides enhanced funding for NASA's core modeling and data assimilation programs, that provide global products such as the Modern-Era Retrospective-Analysis for Research and Applications that can be used in support of national and international assessments, especially as data sets to be used in the quantitative evaluation of global and regional climate models.
- **Accelerated development of technology for future Missions**—The increased funding for the Earth Science Technology Office enabled by the budget will allow increased funding for technology for future Decadal Survey missions, several of which have the potential to provide major advances in resolution of global water stores such as snowpack and groundwater.

After the failure of the OCO launch vehicle, NASA assessed the most efficacious method to collect the CO_2 measurements to meet scientific and societal needs. NASA compared an OCO reflight and an accelerated ASCENDS launch and determined a reflight of the OCO satellite best met the near term needs. This decision was influenced by a combination of technical readiness, relative cost of the missions, and the time to prepare the payload for launch. The President's FY2011 budget request fully funds the OCO-2 mission for an early CY2013 launch. The proposed budget also enables funding for the development and flight of the follow-on CO_2 mission ASCENDS in FY2019.

The OCO-2 mission uses a passive approach, relying on reflected solar radiation as a light source and three high resolution grating spectrometers to monitor spectral bands of CO_2 and O_2 in the mid infrared spectral region. ASCENDS is an active system, currently being designed to use the same spectral channels, using lasers carried as the light source, and monitoring the back reflectance of the laser signals to monitor changes in CO_2. Because there is little backscatter from the atmosphere itself at these wavelengths, the majority of the signal (with the exception of cloudy scenes) would come from reflection off the surface. Hence, the basic observation is essentially the same as that of OCO-2. The primary advantages of the ASCENDS concept is that it would obtain observations at night and would have more sensitivity at high latitudes relative to OCO-2. The measurements from the active ASCENDS instruments would continue and complement the OCO-2 measurements.

NASA, through its Earth Science Technology Office (ESTO) competitive funding line, has invested in a number of technology development studies for the ASCENDS mission. Several of the laser concepts that directly monitor CO_2 bands have shown promise, although the technology for lasers to monitor bands of O_2 are earlier in development. NASA will continue to study the instrument options through FY2010–FY2012. The baseline ASCENDS concept also calls for a passive sensor (like OCO) to monitor atmospheric Carbon Monoxide (CO) as well. There is potential that such a sensor could also monitor atmospheric Methane (CH_4) since it is also an important greenhouse gas. With small changes and technological development, this sensor could also obtain CO_2 observations which would serve to validate the active sensing observations from ASCENDS and serve to properly tie the climate record from OCO-2 to that of ASCENDS.

Surface Water Ocean Topography (SWOT), LRD 2020



The Surface Water Ocean Topography (SWOT), mission will revolutionize knowledge of the surface water inventory on the continents by precise measurement of water levels in some 3 million lakes and water bodies and the discharge of all major rivers. Likewise, SWOT sea surface topography data will illuminate ocean circulation as never before, aiding climate modeling and prediction. The President's FY2011 budget request will enable the start of the SWOT mission, in collaboration with the French space agency CNES, with a launch targeted for 2020.

A significant societal and scientific problem of the 21st century is the supply of fresh water to a global human population growing to nearly 9 billion by mid-century. Knowing precisely where fresh water resides will allow for deeper understanding of the natural water cycle and the informed control of the resource by humans. The SWOT mission will revolutionize knowledge of the surface water inventory on the continents by precise measurement of water levels in some 3 million lakes and water bodies (>250m^2) and the discharge of all major rivers (>100 m wide). No longer will fresh water data be hostage to political boundaries. Likewise, SWOT sea surface topography data will illuminate ocean circulation as never before, aiding climate modeling and prediction. SWOT will provide the first global altimetric measurements of the kinetic energy-containing scales in the ocean—from 10–100km. Ocean eddies that will be resolved by SWOT observations are central to mixing and re-distribution of heat and momentum in the ocean. This knowledge will reduce uncertainty in climate projections.

The key to SWOT's measurement capabilities is a new technique, Ka-band Synthetic Aperture Radar (SAR) interferometry, leveraging several prior NASA technology development investments. The Ka-band SAR Interferometric (KaRIn) system measures in two swaths of 60km each using two antennas separated by a 10m baseline yielding

50m spatial resolution over land and 1km spatial resolution over oceans with 10cm and 1cm height accuracies, respectively. The payload also includes a nadir altimeter, microwave radiometer to correct for wet tropospheric delay in the radar signals, and precision orbit determination (POD) instruments (e.g. GPS, DORIS, LRA). CNES regards SWOT as a very high priority, reflecting a +25 year partnership with NASA in radar altimetry and warranting the support and advocacy of the CNES President. Partnership contributions could include the spacecraft bus, nadir altimeter, DORIS POD instrument, ground data processing, flight operations, and possibly component or subsystems for the KaRIn instrument. These significant contributions make possible a FY2020 launch date for the combined NASA/CNES SWOT mission.

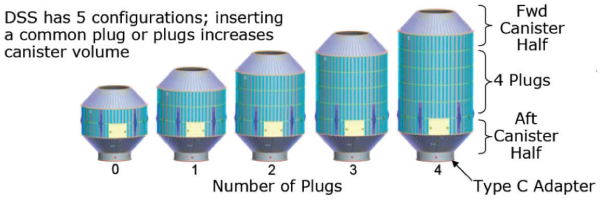
Subsequent Tier 2 Missions

The budget request enables the acceleration of all the Decadal Survey Tier 2 missions. Beyond 2020, NASA anticipates being able to launch missions of this scale at a rate of one per year. NASA will employ the same decision criteria to determine the order in which the balance of Tier 2 missions and the Tier 3 mission should be developed for launch, taking into account science priorities established in coordination with the USGCRP.

2.1.6 Mission Program Infrastructure

The accelerated pace of mission launches and new missions enabled by the President's FY2011 budget request will allow much greater coincident measurement and constellation flying, more robust data continuity for critical climate data records, and more rapid delivery of critical data products to provide societal benefits. Three key investments are required to realize the full potential of this increased flight rate, and NASA will use some of proposed budget to provide this infrastructure enhancement.

Dual Spacecraft System (DSS), LRD 2013



With the President's FY2011 budget request NASA will complete the development of a critical launch vehicle adapter system, the Dual Spacecraft System (DSS), that will allow much more efficient use of the proven and reliable Evolved Expendable Launch Vehicles (EELVs). NASA will immediately contract for the development of the DSS and be ready as early as 2013 to support dual manifests on large EELVs.

The pending retirement of the Delta II hampers NASA's ability to affordably insert medium mass satellites into space until alternate commercial launch vehicles are available and certified. The only currently available commercial launch vehicles that meet the Earth Science requirements for reliability and launch capacity are the Evolved Expendable Launch Vehicles (EELV). The EELVs have substantially greater capacity than any single anticipated Earth science payload. The President's FY2011 budget request supports a significantly increased launch rate for Earth observing satellites, in addition to the Earth Venture class missions planned previously.

EV-2 and EV-4 are expected to be orbital missions of opportunity targeting smaller missions not included in the group of larger facility-class missions called out the Earth Science Decadal Survey. Given the increasing cost associated with access to space for Earth observing satellites, the Dual Satellite System (DSS) proposed by the United Launch Alliance (ULA) provides a gap solution that accommodates the launch of two "medium size" satellites on a single EELV.

The DSS concept provides a capsule with appropriate mechanical and electrical interfaces to allow a second satellite inside the capsule to utilize the unused launch capability of a large EELV. It is based on the proven Dual

Payload Attach Fitting (DPAF) that was used on the Delta II. The current design is at a Critical Design Review stage of readiness. With the resources provided by the President's FY2011 budget request, NASA's Earth Science Division will contract for the completion of the development of the DSS. In order to reach the polar orbits often desired by Earth science satellites, NASA would expect to have a viable fully qualified Dual Launch System available for use starting in 2013.

Standard Instrument to Spacecraft Interfaces

The President's FY2011 budget request enables NASA to initiate several new missions, increase partnerships with other space agencies, and start a series of new competitively selected flight instrument developments. To support these new instrument and partnership activities, with the FY2011 budget request NASA will invest in the necessary system engineering to provide appropriate design and interface guidelines to the instrument developers to ensure the instruments have the maximum potential for flights of opportunity on NASA or partner missions.

With the resources provided by the President's FY2011 budget request, NASA will fund the Venture Class of competitive opportunities, as recommended by the NRC's Earth Science Decadal Survey. The Venture class investigations include sub-orbital, instrument development, and full orbital small satellite missions. For orbital instruments and missions, costs and risks will be reduced by development of standard instrument-to-spacecraft interfaces. These standard interfaces will include power, command and data handling, instrument modes, mechanical mounting, instrument envelopes, fields of view, instrument alignments, attitude errors and disturbances, thermal, monitoring, and environmental conditions. Standards will also be developed for test interfaces and simulators. The guidelines provided through these standards will define a set of interface standards for future Venture Class announcements leading to a Spacecraft Bus Planners Guide.

Standard interfaces across missions provide a path to lower costs and risks from a programmatic, technical, and budgetary perspective. Applying standard interfaces reduces the non-recurring engineering costs associated with developing custom interfaces for each instrument. The costs associated with developing custom spacecraft simulators will also be reduced since a simulator design will be available or simulators provided to the Venture class missions. A standard mounting platform will also be developed and provided to the science investigators. This platform will reduce the risks associated with mechanical and thermal interfaces. A spacecraft bus can be targeted to apply these standards and, from that study, a Spacecraft Bus Planners Guide developed. Risks will be reduced with the increased predictability provided by the spacecraft standards. On the programmatic side, standard interfaces will simplify schedule and budget planning as well as oversight functions since these interfaces will be similar across the projects. Testing plans will be common across the projects since similar plans would be developed out of the codified testing standards. These standards will also aid the independent assessment of each mission since each will be compared against the common benchmark.

This instrument standardization activity will also inform and influence design and interface definitions for instruments built for the Decadal Survey and Climate missions. Conventions will be defined for data formatting to ease the development of multi-instrument and multi-mission combined data products from real and virtual constellations of orbiting satellites. Experience gained from six years operating and utilizing the five satellite afternoon constellation (including Aqua, CloudSat, CALIPSO, PARASOL, and Aura) has revealed the power and benefit of multi-mission integrated products for true Earth-system science development. The instrument standardization activities done during instrument design will further advance this concept.

In early FY2010 NASA contracted for a set of studies with spacecraft vendors to develop options for reducing spacecraft costs for future missions. These included consideration of a single spacecraft procurement for multiple satellites, and a possible definition of a common spacecraft bus. The President's FY2011 budget request provides resources to fund a parallel instrument systems engineering activity to complement the spacecraft work. Together with the additional Earth Venture-class AO call for instruments, the DSS and standard instrument to spacecraft interfaces enable a robust and flexible flight program responsive to emerging science, national needs, and partnership opportunities.

Ground Systems for Mission Operations and Data Management

NASA will accelerate planned upgrades to the existing mission operations, data capture, and critical science data systems to support the acceleration of the Decadal Survey, Venture-Class, and climate continuity missions enabled by the FY2011 President's budget request. These upgrades will ensure that NASA's data system infrastructure keeps pace with the national user community's increasing demand for rapid processing and data availability.

Analysis and planning for the further evolution of NASA's existing mission operations, ground system, networks and science data systems infrastructure has already commenced in response to system challenges created by the NRC Decadal Survey recommendations. The pioneering infrastructure developed in the 1990s to support the Earth Observation Systems Program has provided a unique cross-mission science data and information access system essential to enable integrated Earth System Science. The inclusion of accelerated and new missions' data in NASA's Earth science data and information systems has hastened the need for this evolution for support of these multiple mission and instrument data streams, to be seamlessly combined in Earth science research and climate modeling analyses.

As we move into the Decadal Survey era many existing system components and functions need to be updated and improved, driven by challenging new requirements. Data rates and data volumes will increase dramatically. Key new measurements are being added. The extent of applied uses for the mission data will directly depend on reduced data latency of real-time or near-real-time systems. High availability of data will require significant enhancements to existing science data system processing and distribution infrastructure. Enhanced IT security will also be required to protect spaceborne assets and for securing the high availability of the ground system assets.

NASA uses a design approach that looks ahead of current operating systems capabilities to anticipate system needs through 2020 and beyond. Evolution to future data systems results from analysis of system elements, determining which elements can continue to operate well and the elements that need to be changed or upgraded to keep abreast of demands from science and societal benefit users. To continue to improve system performance, the automated data flow from spacecrafts to data centers must be substantially increased to accommodate these future missions and maximize data utilization. Mission data flows will be assigned to data centers based on research discipline and programmatic contributions, continuing the practice of keeping the data close to its communities. This practice has proven to be a cost effective strategy and contributes to the continued ease of data use for research and applied communities.

Evolving the current ground system architecture with reusable components will reap significant benefits in lower life-cycle costs, especially as missions move into extended operations. Ongoing technology infusion across all system components will ensure lower operating costs and enhanced functionality. Emerging requirements will be accommodated by planned evolution of both mission operation components (command, telemetry and control, command uploads and remote access) and science data systems (science processing, archive and distribution).

2.2 Mission-enabling/Data-exploiting Activities

The mission-enabling/data exploiting portion of the President's FY2011 budget request for NASA's Earth Science Program will be invested in several key areas that will contribute to and benefit from the missions currently operating and under development. In particular, these investments will: provide added near-term return to the Nation through increased global climate research utilizing data from current operating satellites; enhance NASA's essential contribution to national and international environmental assessment activities; and improve the quality of products and services made available to our citizens and those of citizens around the world who will benefit from improved environmental information. Although in total these added resources represent an increase to the existing base of mission-enabling/data exploiting activities, they are targeted in a way that will have a significant impact on the chosen areas of data utilization, synthesis, calibration, and product production.

Specific targets for increased investment include:

- Modeling, assessment, and computing
- Acceleration of operational use of NASA data and models including SERVIR
- Synthesis of NASA Earth science observations
- Calibration of multi-satellite global data sets
- Carbon Monitoring System
- Expanded Technology Program
- Expanded Education and Public Outreach Program

2.2.1 Modeling, Assessment, and Computing

The FY2011 budget request will allow for enhanced participation of NASA modeling groups and funded investigators, bringing NASA observational and model products to the 2013 US Global Change Research Program (USGCRP) National Assessment and the 5th Assessment Report of the Intergovernmental Panel on Climate Change. It will also provide for a near-doubling of the Scientific Computing budget (by FY2015) to significantly enhance NASA's ability to provide hardware, software, and data visualization services for the modeling and assimilation activities carried out at NASA centers and by NASA's funded investigators.

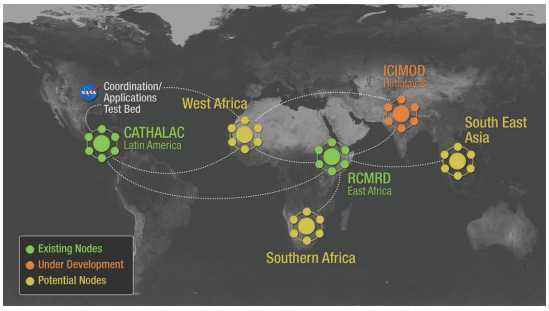
The value of NASA's space-based observations is enhanced by their use in assimilation systems and/or models that produce quantitative data sets on the past and future evolution of the Earth system. These data sets and model outputs constitute two of the linchpins of the assessment activities carried out on behalf of a variety of national and international organizations. These include assessments such as the National Assessment required of the USGCRP under the Global Change Research Act of 1990, the Intergovernmental Panel on Climate Change (IPCC) carried out under the United Nations Framework Convention on Climate Change, and the World Meteorological Organization/United Nations Environment Programme Quadrennial Ozone Assessment. In addition, one-time assessments, such as the Arctic Climate Impact Assessment and Millennium Ecosystem Assessment also rely on modeled projections.

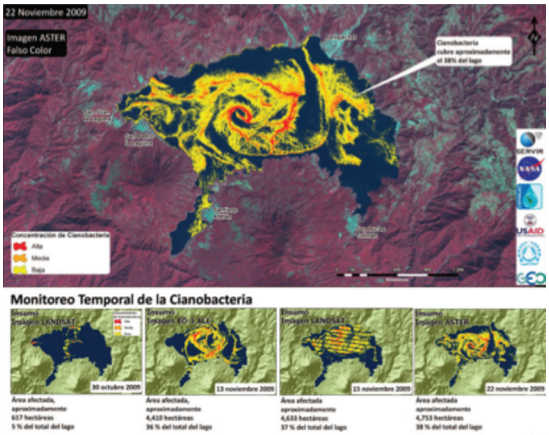
NASA has been a major contributor of models and model-produced data sets for such assessment activities. In particular, the modeling efforts of the Goddard Institute for Space Studies and the Global Modeling and Data Assimilation Office (GMAO) at the Goddard Space Flight Center have been used extensively for such assessments. However, the importance of these assessments and the reliance on them by policymakers is increasing, especially with the increased interest in vulnerability, impacts, and adaptation at regional levels, as well as that of mitigation at global and regional scales. NASA's ability to support these activities is limited by funds (and personnel), and the time is ripe for NASA to increase its investment. Particular areas of emphasis include the following:

- Increased funding for NASA modeling efforts, especially to incorporate advancements in process representation made by NASA scientists and grantees into more comprehensive models, to enhance their ability to contribute as requested to the increasing set of national and international assessments and to broaden the set of assimilated/reanalyzed data sets made available to the research community (e.g., the Modern Era Retrospective Analysis for Research and Applications, the Global Ocean Data Assimilation Experiment).
- A focused solicitation opportunity for participation of the NASA investigator community in near-term assessment activities, most notably the USGCRP National Assessment to be released in 2013.
- Enhanced opportunity for the NASA investigator community to participate in the IPCC assessment, especially in IPCC Working Group 2 which assesses the vulnerability of socio-economic and natural systems to climate change, consequences of change, and options for adaptation, whereas NASA's contribution has

Expansion of SERVIR

With the President's FY11 Budget Request, NASA will form a SERVIR Center for International Satellite Applications and Training, increase nodes in collaboration with USAID, initiate a focus on climate-related applications, create a visiting scientists program, and increase SERVIR's purchase of U.S. commercial remote sensing data.





SERVIR is a regional monitoring and visualization system that uses satellite measurements and other data sources for environmental and disaster management in the developing world. Jointly supported by NASA and USAID, SERVIR currently has nodes in Mesoamerica (node in Panama) and East Africa (node in Nairobi). A node to serve the Hindu Kush Himalaya region is under development. USAID is exploring potential locations for additional nodes in other regions.

SERVIR products are used by government agencies, resource managers, researchers, students, the news media, and the general public. SERVIR-Mesoamerica provided information and detailed maps for 23 earthquakes, hurricanes, floods, and other extreme events in that region from April 2008 through January 2010. SERVIR-Africa assisted regional efforts in 2009 to address flood forecasting, flood mapping, and Rift Valley Fever potential in East Africa and formed a university/student mentor program with projects in 11 east African countries on topics from wildlife populations in Kenya to forest reserve mapping in Malawi.

In response to a request from Guatemala's Ministry of the Environment and Natural Resources (MARN), SERVIR has initiated continuous satellite monitoring of Lake Atitlán, from October 2009 when a very high proliferation of cyanobacteria was detected, through December 2009. SERVIR produced and disseminated analyses based on satellite images captured over the lake, showing trends regarding the lake's contamination. Government institutions, international cooperation agencies and the news media have used the information produced by SERVIR to keep Guatemalan populace aware of the phenomenon, and to initiate recovery of this important water body.

NASA will expand SERVIR to additional nodes in strategic locations in the developing world in collaboration with USAID.

A three-pronged enhancement of SERVIR is enabled by the budget request. First, NASA will form a SERVIR Center for International Satellite Applications and Training, expanding the current US-based SERVIR coordination office at MSFC and increasing its capacity. This Center will serve as a fully functional test bed facility to develop applications and rapidly prototype solutions. The Center will coordinate with each of the SERVIR nodes, foster their development, facilitate collaborations and deployment of innovative applications, and expand the breadth of Earth observation data, modeling capabilities, data integration, and visualization techniques used at the nodes. The Center will conduct training and workshops on domestic and international uses of Earth observations for decision-making. NASA will increase capacity at the Center as the number of SERVIR nodes increases.

Second, NASA will establish a visiting scientist program for SERVIR for researchers and applications specialists from Federal agencies and U.S. universities, broadening the base of products available to SERVIR users and the reach of U.S. international development activities. In the U.S., NASA will form a SERVIR Applied Sciences Team of competitively selected researchers to draw on Earth science and applications expertise in academia and other sectors. SERVIR will substantially increase its purchase of U.S. commercial data products.

Third, NASA and USAID will initiate a major focus on climate-related applications within SERVIR. In support of USAID's climate change program and the international initiative on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD), NASA will create a new effort to work with the SERVIR nodes to incorporate new monitoring applications that track land use change, associated greenhouse gas emissions, and forest carbon stocks. NASA, USAID, and the SERVIR nodes will improve climate projection mapping tools and develop early warning and decision-support tools to support climate adaptation strategies.

been mostly to IPCC Working Group 1 which assesses the physical scientific aspects of the climate system and climate change).

- Enhanced activities in coupling of physical, biological, and other modeling efforts to advance interdisciplinary Earth science research and support integrated assessments and applied knowledge.
- Increased availability of computing capability and software engineering support to enable the NASA research community to produce the required model runs and assimilated/reanalyzed data sets at a frequency and resolution required to participate in the national and international assessments.

2.2.2 Accelerating Operational Use of NASA Data and Models including SERVIR

The FY2011 budget request will provide for significantly enhanced funding targeted to accelerating operational use of the data from current and future NASA research missions.

The data sets and models that NASA produces contribute to improved products and services by NASA's domestic and international partners. In particular, NASA's new global observations improve the quality, coverage, timeliness, and scope of environmentally-focused information products. Such use requires full engagement between NASA and its partners.

NASA currently has several mechanisms in both its research and applied sciences programs to facilitate these efforts. These include:

- Joint Center for Satellite Data Assimilation (JCSDA), a partnership among NASA, NOAA, and DOD to streamline the process by which observations by research satellites become routinely used in NOAA and DoD operational forecasting systems;
- Short-Term Prediction Research and Transition (SPoRT) Center, which provides a way for local weather forecasters to learn how to best utilize NASA satellite data in their forecasting systems;
- Direct Readout Laboratory, in which NASA provides ready-to-use algorithms and assistance to groups around the world who have antennas capable of receiving direct broadcast signals from NASA's Terra, Aqua, and the forthcoming NPP satellites;
- Accelerating Operational Use of Research Data (AOURD) program, first solicited in ROSES 2007 and soon to be competed again via ROSES 2010, which allows for the broader community to participate in the JCSDA and SPoRT activities and also introduce an oceanic component not yet a part of them; and
- The competed programs of the Applied Sciences Program, which provide for community involvement in expanding and supporting the partnerships between NASA and federal, state/regional/local, business, and non-governmental organizations so that they can incorporate NASA data and models in their services and decision making.

This budget request will allow additional efforts related to present and future NASA satellite data sets, increasing the frequency and size of solicitations for the AOURD and Applied Sciences solicitations, and to create a new entity, comparable to JCSDA and SPoRT focusing on ocean products and services, thus complementing the atmospheric emphasis of the existing structures. In addition, NASA will increase funding to the Direct Readout Laboratory to enable it to better serve those users around the world who require access to NASA data in real-time or near-real time as well as access to "quick-look" algorithms that enable that use.

The requested funding for competed activities of the Applied Science Program will be particularly valuable in enabling NASA to increase the number and scope of applications projects and to better extend results to users and state/local/tribal organizations through existing and new partners. The budget request enables the Applied Sciences Program to involve potential users of data from the NRC Earth Science Decadal Survey missions into

early phase planning, so that they are well prepared to utilize the data from these missions as soon as possible after launch. The budget request also allows for enhancement of funding for current successful grantees and, most notably, SERVIR for which there is significant interest among both US government and international partners. The funding specifically enables the SERVIR team to expand their scientific capabilities with a broader set of NASA Earth science products and their service as a test bed for innovative applications, ultimately expanding the use and benefits of NASA Earth Science at SERVIR nodes.

2.2.3 Synthesis of NASA Earth Science Observations

The FY2011 budget request will allow for enhanced synthesis and assessment of data from NASA's currently operating satellite missions, including a ~70% increase in the magnitude of the Interdisciplinary Science (IDS) program by 2015 over that planned for 2011, as well as targeted increases in disciplinary programs and mission science teams with high proposal pressure and corresponding low selection rates.

The current suite of 13 major operating satellite missions for NASA's Earth Science Program, as well as previous missions provides unprecedented data about the Earth system and its changes. These satellites, representing a multi-billion dollar investment over the past two decades, are providing observational information about many aspects of the Earth system never before available on a global basis.

Data from these missions provide a rich source of information for new discoveries about how the Earth system works and how it changes on various time scales. The comprehensiveness of the available data, covering atmospheric, oceanic, terrestrial, cryospheric, and biospheric parameters and the length of data records (in some cases extending up to several decades when combining data from recent and earlier missions as well as operational missions) allows for integrative studies of Earth system variability, forcing, and response. Studies must be carried out in which data and models can be combined together to address the future evolution of the Earth system and the local and regional impacts of global scale climate and other environmental changes.

Studies that take full advantage of the comprehensive nature of the available data frequently require the integration of a range of Earth system science disciplines, and also combine data analysis and modeling. Capturing the talents of multiple investigators requires crossing departmental and/or institutional boundaries. Thus, these integrative studies are best enabled by solicitations allowing for multi-investigator/multi-disciplinary tasks that are larger than most typically solicited by NASA's Earth Science Program.

The Interdisciplinary Science (IDS) program is one key program that accomplishes this integration by incentivizing scientific collaboration. A ~35% increase in selections in the current solicitation and a future smaller solicitation to be released ~18 months earlier than the next planned solicitation are made possible through the budget request. The latter would provide agility and responsiveness for the program to specifically-requested investigations in areas identified as high priority by the US Global Change Research Program (USGCRP), the World Climate Research Programme, and the International Geosphere Biosphere Programme. The results of IDS research form a substantial portion of the basis of international scientific assessments, such as those of the IPCC, on which policy and decision makers rely. The track record of IDS investigations in producing high impact/high visibility results is well recognized and can be expected to grow accordingly in an expanded program.

In addition to augmenting the IDS line, there are certain mission science teams and disciplinary areas within the R&A program that are particularly in need of funding increases given the large proposal pressure reflecting the great interest of the research community for these competitions in the past few years.

Targeted competed research funding will also allow for two specific activities. First, it will allow the extension of a recently-initiated cooperative effort with NASA's Environmental Management Division on the impacts of climate variability and change on NASA's centers and facilities to be broadened to involve the external community through a competitive process. Second, it will support dedicated funding for the analysis and interpretation of data from Operation IceBridge through a competed research opportunity.

2.2.4 Calibration of Multi-satellite Global Data Sets

The FY2011 budget request will provide improved capability for the production of consistent multi-instrument/multi-platform data sets for space-based observations through increases in support for calibration laboratories, facility instruments, ground networks, and airborne calibration, as well as for competed tasks contributing to an interagency national calibration capability. A near-doubling of the annual investment in the space geodesy activity will allow for deployment of next-generation geodetic ground stations to assure accuracy of future altimetric and gravimetric satellite missions.

As the number of providers of global satellite data increases in the future and the reliance of both scientists and policy makers on satellite data increases, it is incumbent on the providers of satellite data to take particular care that the consistency between related data sets is well documented. This is particularly important for studies of Earth system evolution, where data sets constructed from raw measurements made with one or more instruments on different satellites operated by diverse organizations must be combined to create comprehensive data products. An emphasis on calibration and validation throughout all stages of the process is thus required.

The budget request will enable improvements to our national calibration and inter-calibration capability that will allow NASA to work more closely with its international and domestic partners to assure the consistency of data across platforms and the traceability of data to recognized standards. As a result of this effort, the research community will be able to create with greater confidence data sets that fully integrate the data sets of the increasing number of international data set providers. Strong advocacy for increased effort in this area has been provided by the Working Group on Calibration and Validation of the Committee on Earth Observation Satellites, as well as the Global Space-Based Intercalibration System of the World Meteorological Organization.

Specific tasks to be enhanced as part of this activity are:

a. Building a prototype and then multiple copies of the next generation geodetic ground network that includes a new generation of Satellite Laser Ranging, Very Long Baseline Interferometry, and Global Navigation Satellite Systems (GPS, Galileo, GLONASS, Compass). This network of next generation instruments will replace the present aging and deteriorating network that cannot fully support the many geodetic and gravimetric missions that NASA will be implementing (ICESat-2, DESDynI, SWOT, LIST, GRACE FO, GRACE II) as well as its current set of operating missions (especially GRACE, Jason, and OSTM). These missions are particularly important because they provide the observations essential to the measurement and understanding of sea level change due to the transport of water between ice sheets and glaciers, the oceans, and the continental aquifers. The World Climate Research Program publication on sea level change (in press) identifies the need for an improved Terrestrial Reference Frame to be provided by this next generation network as essential for the measurement and understanding of sea level change over multi-decadal time scales. The NASA contribution to the next generation network will be strongly augmented with the significant contributions from other nations (e.g. Australia, Germany, Norway, South Korea, France, and Germany) that participate within the Global Geodetic Observing System (GGOS2020).

b. Enhancing current capability in ground calibration facilities and networks (in addition to the geodetic network) and airborne calibration facility instruments, and expanding their use in validation activities required to establish inter-consistency between data from NASA and non-NASA satellites. Not only will this expanded capability meet expanding needs for calibration and validation, but it will enhance near-term scientific return, contribute to regional monitoring, and provide opportunities for developing countries to participate more fully with NASA.

c. Providing competitive opportunities for the broader NASA investigator community to participate in studies addressing the inter-consistency of satellite data sets in close partnership with our domestic and international partners.

2.2.5 Carbon Monitoring System

The FY2011 budget request will provide for continuation and growth of the Carbon Monitoring System activity begun in FY2010 to provide an improving set of products on carbon storage and exchange between the surface and biosphere for regular delivery to policy and decision-makers, as well as for observing system simulation experiments designed to facilitate development of future carbon monitoring observational capability. This investment leverages the much larger underlying NASA program in Carbon Cycle science.

The FY2010 NASA Appropriation funded NASA to begin work on a Carbon Monitoring System (CMS), including the development of a pre-phase A plan and the results of one or more pilot studies as part of a comprehensive system to provide information about distribution of carbon in the atmosphere, ocean, and biosphere on a range of spatial scales, and to provide information about carbon storage in biomass. NASA has initiated this work building on its global measurement capability for carbon in its various forms and the processes that affect the exchange of carbon between the biosphere, atmosphere, and ocean. As part of the FY2011 budget request, NASA proposes to continue its investment in this area into the future and enhance the use of data from the increasing range of NASA satellites and improvement in NASA's modeling, data assimilation, and systems engineering capabilities to provide improved products in the future.

Other agencies of the federal government will be undertaking related activities in coming years to support national policy objectives (e.g., treaty verification, quantitative analysis of cap-and-trade limits), policy development, and resource management. However, most other agencies will not have the capability of fully utilizing NASA's increasing set of satellite and airborne data, and may not fully utilize the observationally-based advances in carbon modeling and data assimilation that NASA will be creating in coming years. Thus, the continuation of the current effort should allow NASA to fulfill its necessary role in the growing interagency set of activities on carbon monitoring and thus generate better overall products in support of national needs.

2.2.6 Expanded Technology Program

The FY2011 budget request will allow new awards for climate measurements, and will expand validation opportunities that leverage NASA investments and lower the development risk of key components vital for the instruments that will be needed for climate measurements.

Advanced technology plays a major role in enabling Earth research and applications programs by providing the advanced sensors, space systems, and information technologies that enable an improved understanding of the total Earth system. The competed technology programs implemented by the Earth Science Technology Office (ESTO) have achieved considerable success in recent years as evidenced by the number of mission proposals that incorporate ESTO developed technologies. ESTO has long standing working relationships with other NASA technology organizations, other Federal agencies' laboratories, and other partners. ESTO will coordinate with NASA's new Technology Office on areas of common interest.

The Earth Science Technology Program invests in technologies advancing the technological capability of future Earth Science missions. The request will allow expanded and more robust efforts directed toward the Tier 2 and Tier 3 Decadal Survey missions and will make investments in advanced radar, lidar, imagers, spectrometers and radiometers, as shown in Figure 4.

A decade's worth of technology investments are already enabling every mission recommended by the 2007 NRC Decadal Survey. However, a gap often exists between a technology's maturation and its validation as mission-ready. The technology budget will enable many new opportunities for targeted airborne and space-borne demonstrations to significantly reduce the risks of emerging technologies.

FIGURE 4: Mission-enabling technologies NASA is pursuing in support of the Tier 2 and Tier 3 Decadal Survey missions.

Mission	Technology Investments
HysplRI	- Two thermal infrared spectrometer development with airborne demonstrations - Polarization scrambler - On-board processing
ASCENDS	- Two CO2 column lidars - Corrugated mirror telescope - NIR optical receiver
SWOT	- Interferometric SAR - RF hybrid thermal packaging - Water vapor radiometer - Ka-band receiver - Large aperture, deployable reflector - Deployable, Ka-band reflect array
GEO-CAPE	- CO gas correlation radiometer - Panchromatic FTS - Polarization scrambler - VNIR-blind focal plane array - Readout integrated circuit
ACE	- Polarimetric aerosol imager - Cloud profiling radar - Ocean color radiometer - Corrogated mirror telescope - Ka/W-band large deployable reflector - Polarization scrambler - Aerosol lidar detector - On-board processing
LIST	- Swath-mapping lidar - Corrugated mirror telescope array - Optical receiver
PATH	- Microwave sounder - Large aperture, deployable reflector
GRACE-II	- Laser frequency stabilization
SCLP	- X-band phased array - Large aperture, deployable reflector
GACM	- Microwave limb sounder - Corrugated mirror telescope array - Spectrometer - Analog to digital converter for UV to mid-IR
3D-Winds	- Two doppler lidars - Corrugated mirror telescope array - NIR optical receiver, lidar - Doppler wind lidar transceiver - Cloud aersol lidar detectors - RF ASIC for digital beamforming

The FY2011 budget request will be applied in two primary areas:

- New awards for technology development related to climate measurements,
- Collaborations with the broader climate community to acquire comparative flight data and to validate key components of new technologies.

The results of this funding will be an expanded program of technology research for Earth Science, with an increasing emphasis on climate measurements, and a wider range of innovative partnering opportunities in airborne demonstration and flight validation campaigns that help to reduce the cost and risk of new flight missions by providing more mature instruments.

2.2.7 Expanded Education and Public Outreach Program (including GLOBE)

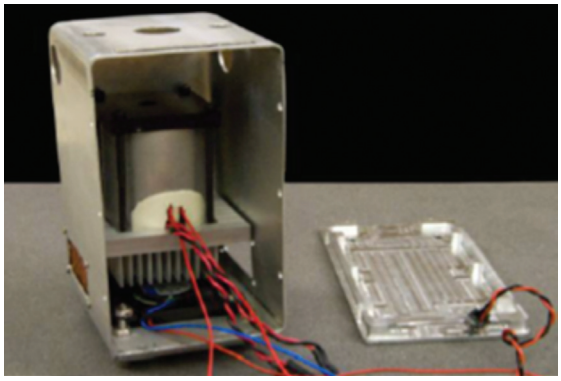
The FY2011 budget request will allow for a targeted increase in NASA's investment in the Global Learning and Observations to Benefit the Environment (GLOBE) program, as well as increased support for competitive activities carried out through educational institutions, professional societies, and non-governmental organizations.

NASA provides data, models, and visualizations to describe the Earth system. The Obama Administration's initiatives to strengthen public literacy about climate change and its implications for society challenge NASA to increase utilization of its results and capabilities for formal and informal education. The FY2011 budget provides resources that will be made available to educational institutions, professional organizations, and non-governmental organizations to engage them more fully with NASA in enabling better public awareness of NASA's unique capabilities.

Expansion of NASA's support of the Global Learning and Observations to Benefit the Environment (GLOBE) program will extend the benefits of this very successful program, which already involves 112 countries and 136 U.S. partner institutions, and has contributed more than 16 million student-made measurements to the available set of global environmental measurements. GLOBE recently began a Student Climate Research Campaign (SCRC), and NASA recently selected four of

Technology Validation Supporting Radiation Science

Detailed observations of the Earth's radiation balance will be an important component of any future climate observing system. A key challenge for the radiation science mission Climate Absolute Radiance and Refractivity Observatory (CLARREO) is extremely precise absolute calibration of the sensors. Temperature must be monitored to better than 0.01 Kelvin over the life of the mission. One technique that is being investigated by CLARREO to periodically recalibrate the on-board sensors is melt cell technology. However, this technology has never been tested in space. Through a partnering arrangement that uses the International Space Station as a validation platform, an ESTO project will provide the first ever demonstration of the viability of melt cells in a space environment.



Images: Melt cell technology. Melt cells contain materials that provide temperature calibration by nature of their precise phase change characteristics. Left image: Two space flight cells (next to dime, for size reference). The melt cells will be placed in a special container (right image) before being sent the International Space Station.

These increased investments for technology will lead to new measurement concepts, provide more mature instruments and enable flight demonstrations of newly developed instruments and components increasing technological maturity and reducing implementation cost and risk for future space missions.

its scientists to participate actively in the SCRC. Support for GLOBE provided in the FY2011 budget request will allow the program to capitalize on available opportunities, especially those associated with the SCRC. Specifically, the budget request will help NASA's scientists and grantees provide a global context for the local observations made by students and enable them to interact more closely with GLOBE's students, teachers, and leaders to make today's cutting-edge space-based scientific results more accessible to them.

3. Assembling the Components to Meet National Needs

Analogous to the combination of the various processes such as atmospheric transport, ocean circulation, biospheric seasonal cycles and others to yield the Earth system, the components of missions and research endeavors above are assembled in various was to address pressing national needs. This section describes four key areas of national need and how key NASA's mission and research programs are integrated to meet them.

3.1 Climate Monitoring and Research

Satellites provide global or near-global coverage using a small number of instruments, allowing for consistent, well-calibrated, and equivalent-quality data to be obtained most anywhere in the world. A major scientific challenge for climate research is to create multi-instrument/multi-platform data sets to span the multi-decadal time scales of interest, and to combine these data with those from in-situ and surface-based observing systems to improve process understanding and climate models.

While the Earth Science research community has demonstrated enormous capability and creativity in producing such data sets using a combination of research and operational data sets, there is a continuing challenge in assuring the adequacy of the satellite data record for climate trend determination. In the last fifteen years in the US, it was assumed that long-term continuity for space-based observations would result from operational entities quickly and effectively continuing data records initiated by research satellites. This approach has not been fully successful.

As a result, there is a need for NASA to assure the continuity of key data sets, especially those which do not directly and substantially contribute to routine short-term forecasts. This cannot be an all-encompassing requirement, but is one in which NASA focuses on those data sets which it initiated, which it has unique expertise in measuring, which its partners are unlikely to be providing in the near-term. Even the FY2011 budget does not allow NASA to indefinitely continue all of the measurements it has demonstrated over the past decades. NASA will base its investments in measurement continuity based on scientific priorities, Administration objectives, technical maturity, and partnership opportunities.

The FY2011 budget request allows NASA to continue a selected number of space-based observations in a way that will be suitable for trend determination into the future:

- **Atmospheric carbon dioxide monitoring**—The space-based measurement of atmospheric carbon dioxide distributions (focusing on measurement approaches sensitive to CO_2 in the lower layers of the atmosphere and, especially, the important atmospheric boundary layer) by NASA will begin with the launch of the Orbiting Carbon Observatory (OCO-2) in 2013. As part of its development of the OCO-2 mission, NASA will procure a full set of instrument spares that, upon the successful launch of the OCO-2 mission will be assembled into a stand-alone OCO-3 instrument. The OCO-3 instrument will be available for flight as a mission of opportunity as early as 2015. During this time period, NASA will initiate full-scale development of the Tier 2 Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission, a lidar-based approach with launch planned for 2019. NASA is currently making significant investments in the Lidar technology that will allow this mission to take place. Along with the satellite missions and technology development, the budget request allows NASA to invest in a software and analysis system that will allow it to regularly produce products optimized to meet policy and decision-making needs for information on the exchange of CO_2 between the atmosphere and the surface, including spatially and temporally-resolved integrated emission and uptake estimates. Corresponding estimates at regional scales of biomass, will be based on NASA's observations of aboveground biomass, including observations from the Ice, Cloud and Land Elevation Satellite -2, ICESat-2,

and the Deformation, Ecosystem Structure and Dynamics of Ice, or DESDynI, missions, launched in 2015 and 2017 respectively. The DESDynI mission will be accelerated at least two years due to the President's enhanced FY2011 budget request.

- **Gravity Field Measurement**—The space-based measurement of ice sheet mass pioneered by the Gravity Recovery and Climate (GRACE) mission launched in 2002 will be extended by the GRACE Follow-on mission to be launched in 2015 in partnership with DLR. The gravimetric measurements made by the GRACE team are highly specialized and not easily made by other space research agencies, especially in a way that would assure traceability to the original GRACE observations and thus allow for relatively straightforward intercomparisons between GRACE and GRACE FO data. Along with NASA's investment in the GRACE FO mission, it will significantly enhance the surface-based global geodetic network that provides the Terrestrial Reference Frame needed for all space-based gravimetric and altimetric missions.

- **Atmospheric aerosol and ocean biology/biogeochemistry monitoring**—The space-based measurements of these quantities has been pioneered by NASA through its launch of the Moderate Resolution SpectroRadiometer (MODIS) instruments aboard its Terra and Aqua spacecraft (1999, 2002, respectively) as well as its scientific support for the commercial Sea-viewing Wide Field-of-view Sensor (SeaWiFS) instrument that flies aboard GeoEye's SeaStar spacecraft. The FY2011 budget request will allow NASA to provide for early flight of a highly calibrated Ocean Ecosystem Spectroradiometer (OES) designed to provide climate-quality radiances that can be used to make quantitative measurements of ocean productivity and related parameters (the "ocean color product suite"). The exacting requirements for this measurement, including precise radiometry, intensive calibration/validation, well-documented algorithms, and the use of ancillary data make this one that is best led by the highly experienced NASA community. The need for additional measurements of ocean color parameters was clearly stated by the National Research Council in its 2008 report *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring*. The instrument has the potential to be a first copy of a radiometer required as part of the Aerosol, Cloud, and Ocean Ecosystem (ACE) mission, which is in the second tier of Decadal Survey missions. This instrument might also fly with a French-built polarimeter (planned for launch in 2018), which would help extend the aerosol polarimetry record started with the French POLDER instrument and which will be continued and significantly enhanced by NASA's Glory satellite; the aerosol and ocean-color measurements are complementary and benefit from being made concurrently.

- **High resolution vertical profiling of atmospheric ozone**—The high resolution (3Km or better) vertical profiling of atmospheric ozone throughout the stratosphere is an important activity, needed to assess the recovery of the ozone layer as it responds both to reductions in surface-based emission of ozone-depleting substances under the Montreal Protocol on Substances that Deplete the Ozone Layer and its modifications, and climate change, that has the potential to affect the transport of trace gases and energy between the troposphere and stratosphere. NASA has provided a long record of high resolution vertical profiling since the 1980s with the Stratospheric Aerosol and Gas Experiment (SAGE) satellites, the Halogen Occultation Experiment (HALOE) instrument aboard the Upper Atmospheric Research Satellite (UARS), and the Microwave Limb Sounder (MLS) instruments aboard both UARS and the Earth Observing System's Aura platform. Together with NOAA, NASA is also supporting the flight of the limb sensor of the Ozone Mapping Profiling Suite (OMPS) instrument aboard the NPOESS Preparatory Project. However, there are no current plans to continue the flight of the OMPS limb sensor aboard any future polar-orbiting operational environmental satellites. To assure continuation of the data record of high vertical resolution profile ozone data, NASA will fly a copy of its previously flown SAGE-III instrument aboard the International Space Station (ISS) beginning in 2013, assuming appropriate launch capability can be obtained. The inclined orbit (~51.5 degrees) of ISS is well suited for obtaining latitudinal distributions of nitrogen dioxide using SAGE III's primary solar occulta-

tion viewing mode. The vertical resolution is especially important in obtaining ozone profile changes below its maximum, where vertical gradients are strong and sensitivity to changes in climate and concentration of ozone-destroying gases is high.

- **Trend Determination, Assimilation and Observationally-Based Modeling of Long-Term Climate Evolution**—The full value of new data coming from NASA satellites is realized only when those data sets are combined to produce accurate multi-instrument/multi-platform/multi-year data sets suitable for trend determination and when they are assimilated through global models to produce global data sets. The data sets (either as retrieved or assimilated data sets) NASA produces can be used for initialization, spatially and temporally accurate representation of forcings, and evaluation of global climate models. The long-term data sets of climatically important variables that will come from these efforts can be especially important in national and international assessments, most notably those of the Intergovernmental Panel on Climate Change. The budget request will provide additional support to the Global Modeling and Assimilation Office (GMAO) and Goddard Institute for Space Studies (GISS) that will enable NASA to produce more assimilated data sets and climate forecasts fur use by the research and assessment communities.

3.2 Carbon Cycle Research, Monitoring, and Product Generation

The connections among global climate change, the climate forcing of radiatively-active trace gases and aerosols (especially the carbon-containing gases carbon dioxide and methane, as well as black carbon), global land cover and land use change, and the global carbon cycle that redistributes carbon between the atmosphere and the terrestrial and marine biosphere are well established. In order for us to predict with confidence the future evolution of the Earth's climate, we need to have the capability to predict accurately the partitioning of carbon among the atmosphere, ocean, and biosphere. International recognition of the importance of industrial and biological emission and uptake of carbon-containing gases and aerosols has led to the development of a policy and regulatory environment in which quantitative and verifiable knowledge about the spatial and temporal distribution of carbon emission and uptake, as well as biomass, is needed at both global and regional scales. A combination of space-based, in-situ, and system based observations can meet this need.

The global viewpoint of space provides a unique opportunity to obtain globally consistent data about the distributions of carbon in the atmosphere, ocean, and biosphere, and to understand the processes that connect them. NASA has long been making observations and conducting research in this area, documenting the spatial and temporal evolution of land cover, biological productivity (i.e., carbon fixation by photosynthetic organisms in both marine and terrestrial), and distribution of trace gases and aerosols. The FY11 budget request allows us to add new global observational capability, accelerate previously planned enhancements in capability, and sustain the development of an integrated effort to provide integrated national and global products on distributions of carbon. Specifics include:

- **Observations of Atmospheric Carbon Dioxide**—The budget request supports the launch of two evolutionary missions focused on measuring the distribution of carbon dioxide, with sensitivity to the atmospheric boundary layer. The first, OCO-2 (2013 planned launch), will use a passive technique for daytime-only observations, while the latter, ASCENDS (2019 planned launch—a Tier 2 Decadal Survey mission), will use an active technique that makes both daytime and nighttime observations. In addition, a copy of the OCO-2 instrument will be built in sequence with that for the OCO-2 mission, allowing for use on a flight of opportunity between 2015 and 2019, or its inclusion on the ASCENDS mission. As a result of these efforts, the availability of improving measurement capability for space-based atmospheric CO_2 throughout much or all of the decade beginning in 2013 is established.

- **Measurements of Terrestrial Aboveground Biomass**—The budget request accelerates the launch of the DESDynI mission, with both its radar and lidar components now planned for launch in 2017. The ICESat-2 mission, launching in 2015, although optimized for study of polar ice will also make global, moderate resolution measurements of vegetation height. With the launch of DESDynI in 2017, NASA will be providing significant amounts of data on vegetation height, the vertical distribution of biomass in forests, and total aboveground biomass beginning in 2017.

- **Measurements of Oceanic Productivity**—The budget request allows for the launch of the Pre-Aerosol, Clouds, and Ocean Ecosystem (PACE) mission in 2018. This mission will include a radiometer optimized for studies of ocean productivity (most likely accompanied by a polarimeter to provide information on atmospheric aerosol distributions, which is important for quantitatively accounting for aerosol impacts on ocean surface emitted radiances). These data will extend the high quality observations on ocean productivity begun by NASA in the late 1990s with the SeaWiFS and MODIS instruments. The specific focus of this mission on ocean productivity measurements will enable improved observations more suitable for the creation of the multi-instrument/multi-platform data sets than those observations likely to be available in this time frame from satellites of other agencies (e.g., ISRO, ESA) because of NASA's documented experience in radiometry, algorithms, and calibration/validation. These measurements are important for quantifying carbon dynamics in the ocean.

- **Development and Evolution of Observationally-Based Carbon Cycle Products**—The societal interest in information on distribution of carbon storage and emission/uptake is an important driver for the production of data sets that utilize the full range of available data and clearly tie observed quantities (such as biomass and atmospheric CO_2 distributions) to desired quantities (esp. carbon emission and sequestration amounts). NASA's underlying investment in carbon observations, modeling, and data assimilation provides the basis for the FY11 budget request to integrate the new data with existing capabilities to produce needed products and support their quantitative evaluation by the scientific community. This analysis system can also provide information on how the improvements in observational capability provided by NASA and its partners (enhanced significantly by the budget request) can translate into improvements in the availability of improved carbon storage and emission products in the future. In the period before NASA's new observational data can be used in product production, attention will be focused on use of currently available NASA data (e.g., Landsat and MODIS for forest disturbance and recovery impact on carbon emission/uptake, ICESat estimates of forest height in selected regions of the world, and MODIS/SeaWiFS estimates of marine productivity) as well as that from its international partners (e.g., the Japanese Space Agency's GOSAT measurements of tropospheric CO_2, and ALOS PALSAR estimates of biomass).

3.3 Enabling the 2013 US National Assessment

The observations, models, and research that NASA provides can make significant contributions to the forthcoming National Assessment (due date May, 2013) required under the Global Change Act (GCRA) of 1990. This assessment follows in the series of previous assessment documents created by the US Global Change Research Program (USGCRP) or its immediate predecessor, the Climate Change Science Program (CCSP). These include the report *Impacts of Global Climate Change in the United States* (2009), the *Scientific Assessment of the Effects of Global Change on the United States* (2008), the series 21 Synthesis and Assessment Products released by the CCSP (2006–2009), and the report from the National Assessment Synthesis Team: *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change* (2001).

The FY11 budget request will enable NASA to target a significant effort directly in support of the forthcoming US National Assessment while continuing its support for others, most notably the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and the quadrennial Ozone Assessment of the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). In providing its support for national and international assessments, NASA works closely with other USGCRP agencies and the assessments' respective steering committees to assure that NASA's observations, models, and community of researchers are well positioned to contribute to the assessments. Building on early and on-going research solicitations, investigator participation, and workshop organization, the budget request allows NASA to enhance efforts in each of these areas.

For the National Assessment, NASA is in particularly close consultation with the USGCRP, and will be actively participating in its development. Avenues in which NASA expects to contribute include:

- **Availability of NASA model runs and data sets for use in the assessment**—In the course of carrying out assessments, multiple model runs and/or data sets are utilized to document prior Earth system evolution and make predictions about its future evolution. Where appropriate, NASA models will be run to support the assessment, and data sets (either directly retrieved or assimilated) will be provided for the assessment. These data sets will play a particularly important role as providing observations to support model-observation intercomparisons (to accompany the well-established model-model intercomparisons that are found in most assessments).

- **Analysis of existing data sets and models**—The NASA-funded community of investigators is well positioned to look closely at the long-term record of satellite and relevant surface-based and/or in situ data to study the evolution of the Earth system. While historically, a primary focus of NASA's efforts has been global, enhanced attention can be paid to the US for the national assessment. Such activities can be done both through our Research and Analysis (R&A) Program and our Applied Sciences Program (ASP), with ASP typically focusing on more regionally- and sectorally-specific aspects, and R&A emphasizing the broader global environment and the connections between larger-scale processes (e.g., the connection between physical forcing and biological response, and vice versa).

- **Focused involvement of NASA-supported investigators in the assessment**—NASA scientists (including both its center scientists and its grantees) can take on significant roles, including leadership roles in an assessment. This has been traditionally true for the WMO/UNEP ozone assessment, in which NASA support has allowed the active involvement of numerous chapter authors (and currently supports one of the current Assessment co-chairs), as well as the IPCC assessment (for example, in the 4th Assessment Report, NASA provided funding to specifically support the role of one of its scientists as a Convening Lead Author in Working Group 2). As the National Assessment becomes better defined by OSTP/USGCRP, NASA will be able to provide added support for its scientists and grantees taking on leadership roles that will require a significant fraction of their time.

- **Facilitating community interactions**—NASA can support the organization of workshops specifically directed towards the National Assessment and the involvement of NASA models, data, and researchers, as well as broader-community based activities that will enable research, applications, and adaptation communities to organize more effectively its involvement in the National Assessment. These may be based regionally, sectorally, or around broader scientific themes.

3.4 Rapid Response to Science Results and Partnership Opportunities

The combination of Climate Continuity missions and new measurement missions provide the observational basis for climate change research and the broader study of Earth as a system. The combination of Venture class instruments of opportunity, Dual Satellite System, and standard instrument-to-spacecraft interfaces adds a robustness and flexibility to the overall observing system. This facilitates international partnerships by widening windows of schedule compatibility and reducing the complexity of interfaces. It also provides the means to overcome mismatches between long dedicated mission development times and changing scientific or applications needs. Analogously, robust interdisciplinary science investigations and data assimilation and modeling programs identify and respond to new scientific discoveries and new applications of Earth science data and results.

4. Conclusion

The 2007 NRC Decadal Survey recommended that NASA implement a robust suite of 15 missions designed to investigate many fundamental scientific questions about the Earth system, a competitive Venture class program of low-cost missions, and expanded research, applications, and technology development efforts. The significant funding provided in the FY2011 budget request presents an opportunity to accelerate and enhance NASA's efforts in these areas and add capabilities to assure continuity of key climate data sets, while maintaining a balanced and robust program that is responsive to national needs. This represents a climate-centric restructuring of how NASA plans to implement the Decadal Survey recommendations and address one of the most pressing scientific and societal challenges of our time.

Appendices

Appendix A: Earth Science Foundational Missions

With the President's FY2011 budget request, NASA's Earth Science Program is implementing a balanced and robust plan to accomplish a broad sweep of critical Earth observation measurements. Currently in development are the Foundational missions, identified by the NRC Earth Science Decadal Survey as necessary precursors to the new measurements to be flown on subsequent missions. These foundational missions include Glory, Aquarius, NPOESS Preparatory Project (NPP), Landsat Data Continuity Mission (LDCM), and the Global Precipitation Measurement (GPM). Within the last year all foundational missions have made significant progress toward their launches.

The Glory project accepted delivery of the primary observatory instrument, the Aerosol Polarimetry Sensor (APS) from the vendor and successfully integrated it to the spacecraft. The mission team is in the final steps of correcting a flawed spacecraft main computer board problem that was identified late in the spacecraft development cycle. Final observatory acceptance testing with both the APS and the Total Irradiance Monitor (TIM) instruments is ongoing, and with the delivery of the rebuilt spacecraft computer the Observatory will be ready for a launch at the start of FY2011, in November 2010. Included in the Earth Science plan is funding for the Glory mission operations and data analysis (MO&DA) for the full anticipated mission lifetime.

At the start of FY2010 the NASA-provided Aquarius instrument was successfully integrated to the Argentine National Commission for Space Activities, CONAE-provided spacecraft. All other instruments and spacecraft components have been delivered to the Observatory by the 2nd quarter of FY2010, and the observatory integration is now complete. Final observatory testing is underway, leading to an Aquarius/SAC-D launch in FY2011. Included in the Earth Science plan is funding for the Aquarius instrument science operations and data analysis for the full anticipated mission lifetime.

The NPOESS Preparatory Program (NPP) mission finally accepted delivery of the long-delayed VIIRS instrument and integrated it successfully to the NPP spacecraft. Full NPP observatory-level testing will commence with the arrival of the final instrument the Cross Track Infrared Sounder, CrIS, in the summer of 2010, leading to a launch at the end of FY2011.

The Landsat Data Continuity Mission (LDCM) completed its KDP-C Confirmation review in December 2009, establishing its formal cost and schedule commitment for the mission. Prior to the Confirmation review the Thermal Infrared Sensor (TIRS) instrument was fully integrated into the baseline LDCM mission, following an aggressive and successful accelerated Phase B for the TIRS instrument. NASA authorized the contract for the LDCM launch vehicle in December and with that decision NASA and its mission partner the US Geological Survey (USGS) are together moving forward for a December 2012 launch.

At the start of FY2010 the Global Precipitation Measurement (GPM) mission also completed its formal KDP-C confirmation review, likewise establishing the formal cost and schedule commitments for the mission. The formal partnership with JAXA was confirmed with the signing of the NASA-JAXA MOU. The GPM completed its mission Critical Design Review (CDR) in December 2009, and continues to make steady progress towards a July 2013 launch from JAXA's Tanegashima Space Center. Included in the Earth Science plan is funding for the GPM mission operations and data analysis (MO&DA) for the full anticipated mission lifetime.

Appendix B: Mission Cost Estimation

NASA has developed the budget for this program and for the missions that are the essential elements of the program using a variety of different input data for the missions. The different methods used include:

1. Grass roots cost estimates gathered by mission study teams, usually supported by a NASA Center-based instrument or mission integrated design capability (referred to as **MDL**, or Mission Design Lab);
2. Analogy-based cost models based on the similarity of mission to previously missions NASA has developed (referred to as **Analogy**);
3. Direct comparison with a previous build of a mission of very similar nature (referred to as **Redo**); or
4. Some combination of the above.

In some limited cases vendor supplied estimates or quotes were included.

These different price estimating methods include recommended project level cost and schedule reserves. None of these methods provides guidelines for program level reserves, or recommendations that such reserves be added to the mission budget. NASA's experience has been that such program reserves above and beyond the project defined reserves are needed to complete the missions in the face of technical challenges and externally driven schedule changes. For each mission in the program we have included additional program level reserves above the Project level reserves in the estimated budgets.

Each mission has unique characteristics or previous heritage that makes defining a single consistent program reserves posture for all inappropriate. For each mission we have considered these individual factors and tailored the recommended reserves and cost assessment methodology accordingly. Table B1 identifies the approach taken for each mission. The indicated Project contingency is applied as a multiplier to the individual cost estimates, and the Program contingency is a multiplier to the total Project estimate (Grass roots cost + Project level contingency). The total estimated mission cost is the sum of the three: Mission Costs = Mission Estimate + Project Contingency + Program Contingency.

Experience has shown that NASA missions last for many years beyond the prime mission phase. Throughout the program we have included mission operations and data analysis for multiple extensions beyond the primary mission phase.

All costs are estimates only. NASA will commit to a mission development cost at the KDP-C confirmation review for each mission.

	Contingency Percentage		
Mission	**Project Level**	**Program Level**	**Comment**
OCO-2	25%	30%	Redo. Program reserves set by aggressive development schedule to recover measurement on orbit soonest
OCO-3	25%	50%	Analogy/Rebuild. Instrument only, with redesign required for new interfaces.
DESDynI-R	–	15%	Analogy/MDL. Mission team is revising mission requirements and implementation to meet cost constrained guidelines.
DESDynI-L	–	15%	Analogy/MDL. Mission team is revising mission requirements and implementation to meet cost constrained guidelines.
CLARREO-1	–	15%	Analogy/MDL. Mission team is revising mission requirements and implementation to meet cost constrained guidelines.
CLARREO-2	–	15%	Analogy/MDL. Mission team is revising mission requirements and implementation to meet cost constrained guidelines.
SAGE III	23%	15%	Redo. Refurbishment of existing instrument, with some new contracts required.
GRACE FO	25%–30%	30%	Redo/MDL. Different reserves carried for spacecraft (30%) and remainder of development (25%)
PACE	30%	15%	MDL/Analogy. Design Lab runs of similar missions, analogy for descoped or simplified elements
ASCENDS	25%	15%	MDL. Mission science and instruments still in definition, extensive technology development ongoing outside of mission.
SWOT	25%	30%	MDL/Analogy. Design lab runs and great similarity to Jason missions.
DSS	None	50%	Analogy. Estimate based on vendor ROM for Dual Spacecraft Support.

Appendix C: Table of Missions, Observations, and Societal Benefits

Mission Lines	Launch Readiness Date	Partner	Observed Quantities	Scientific Issues	Societal Benefit (Decadal Survey Theme)
Glory	Nov 2010		Aerosol polarimetry, Total Solar Irradiance	Direct and indirect radiative forcing from atmospheric aerosols, solar forcing of climate	Clouds and Aerosols (Climate), Aerosol-cloud discovery, Tropospheric aerosol characterization (Weather)
Aquarius	Apr 2011	CONAE	Sea surface salinity	Oceanic three-dimensional circulation	Ocean circulation, heat storage, and climate forcing (Climate)
NPP	NET Sep 2011	NOAA	Continuation of imaging, sounding, ozone, and radiation budget from EOS sensors	Long-term trend documentation of changes inland surface, ocean, and atmosphere	Clouds, Aerosols, Ice, and Carbon (Climate), Ecosystem Function (Ecosystem), Ozone Processes (Health)
LDCM	Dec 2012 (ext. comm. Jun 2013)	USGS	Land Cover/Land Use, thermal infrared surface properties	Long-term trends in land cover and land use	Land cover, Ecosystem composition , Algal blooms and waterborne infectious diseases, Vector-borne and zoonotic disease (Health),
OCO-2	Feb 2013		Atmospheric CO_2 dry air column Mole Fraction	Measurements of atmospheric CO_2 to locate and quantify carbon sources and sinks	Carbon budget (Ecosystem)
GPM-Core	Jul 2013	JAXA	Precipitation	Determination of global precipitation amount and type with 3 hour resolution	Heat stress and drought (Health), Precipitation (Climate), All-weather temperature and humidity profiles (Weather), Surface water and ocean topography (Water)
SAGE III/ISS	May 2014 (instrument available)	SOMD	Vertical profiles of ozone, aerosols, water vapor in stratosphere and upper troposphere	Documentation of vertical dependence of ozone recovery, aerosol layer evolution	Ozone processes (health), Clouds and Aerosols (Climate)
SMAP	Nov 2014		Soil moisture, freeze-thaw state	Quantification of soil moisture and freeze-thaw state of surface	Heat stress and drought, Algal blooms and waterborne infectious disease, Vector-borne and zoontic disease (Health); Soil moisture and freeze-thaw state, surface water and ocean topography (Water)
ICESat 2	Oct 2015		Ice sheet thickness, sea ice thickness, vegetation height	Document changes in ice distributions at high latitudes and measure vegetation height	Clouds, Aerosols, Ice, and Carbon (Climate), Ecosystem Structure and Biomass (Ecosystem), Sea ice thickness, glacier surface elevation, glacier velocity (Water)
GRACE FO	2016	DLR	Time variable gravity, including mass of ice and water	Documentation of changes in mass of ice sheets, stored ground water, and Earth's gravitational field	Ocean circulation, heat storage, and climate forcing (Climate), Groundwater storage, ice sheet mass balance, ocean mass (Water)

Mission Lines	Launch Readiness Date	Partner	Observed Quantities	Scientific Issues	Societal Benefit (Decadal Survey Theme)
OCO-3	2015 (instrument available)		Atmospheric CO_2 dry air column Mole Fraction	Measurements of atmospheric CO_2 to locate and quantify carbon sources and sinks	Carbon budget (ecosystem)
CLARREO-1	Nov 2017	NOAA (coordinated missions)	Spectrally-resolved calibrated Earth radiances	Creation of reference Earth spectra for comparison with climate models to fingerprint changes in Earth energy budget	Radiance Calibration (Climate), Ozone Processes (Health)
DESDynI Radar and Lidar	Nov 2017	DLR?	Earth surface deformation; vegetation height, canopy volume, and vertical profiles of biomass; motions of ice	Motions of the Earth surface (including those associated with volcanos, earthquakes, other natural and man-made hazards), and ice sheets; terrestrial carbon storage and habitat change	Ice Dynamics (Climate), Ecosystem Structure, Biomass, and Biodiversity (Ecosystem Climate), Heat Stress and Drought, Vector borne and zoonotic Disease (Health), Surface Deformation (Solid Earth), Sea ice thickness, glacier surface elevation, glacier velocity (Water)
PACE	2018	CNES/ESA?	UV-Vis-SWIR wide swath measurements of: water-leaving radiance (ocean color radiometry), phytoplankton chl a, carbon stocks and ocean carbon uptake; ocean ecosystems, plankton physiology; aerosol and cloud optical depth; some aerosol and cloud properties via spectral and polarimetric observations	Quantifying carbon budget (stocks, fluxes, monitoring and content in the ocean ecosystem); ecosystem health; plankton physiological status and climate impacts; ocean physical-biological interactions; land/sea carbon exchange, coastal water quality, HABs, and impact of natural and other hazards on ocean ecology; geographical distributions of cloud and aerosol properties	Carbon in the ocean ecosystem (Climate); global ocean productivity (Ecosystems); Harmful Algae Blooms (HABs) (Health)
ASCENDS	2019		Atmospheric CO_2 dry air column Mole Fraction (day and night)	Improved identification and quantification (including day/night) of regional sources and sinks of atmospheric CO_2	Carbon budget (Ecosystem Climate), Ozone processes (Health)
SWOT	2020	CNES/USGS?	Lake levels (3 million lakes), River discharges, and Km-scale ocean surface topography	Enables budgets of surface fresh water on the continents and examination of kinetic energy containing scales in the ocean	Surface Water and Ocean Topography (Water), Ocean circulation, heat storage, and climate forcing (Climate)
CLARREO-2	2020		Spectrally-resolved calibrated Earth radiances	Extension/expansion of reference Earth spectra for comparison with climate models to fingerprint changed in Earth energy budget	Radiance Calibration (Climate), Ozone Processes (Health)

Appendix C Continued

Mission Lines	Launch Readiness Date	Partner	Observed Quantities	Scientific Issues	Societal Benefit (Decadal Survey Theme)
HysPIRI	>2020	USGS?	Global distribution, composition & condition of terrestrial & shallow aquatic ecosystems; fire fuel status, fire occurrence/severity/recovery patterns; global distribution of surface mineral resources; improve volcanic hazard prediction & impact assessment	Global full VSWIR spectra & multispectral thermal imagery of the Earth's surface on a seasonal basis at landscape scale—essential data for taking next steps in full Earth system and climate modeling	Ecosystem function (Ecosystems), Heat stress and drought, Vector-borne and zoonotic diseases (Health), Surface composition and thermal properties (Solid Earth, Water)
GeoCAPE	>2020	KARI?	Continuous tropospheric O_3, aerosol, CO, NO_2, HCHO, SO_2 column densities; coastal chlorophyll, particulate and dissolved organic matter, turbidity, phytoplankton	Emissions, transformation, and transport of species determining air quality and short-lived climate forcing; impacts of climate change, anthropogenic activity, and short-term events on marine ecosystems including primary productivity	Global ecosystem dynamics (Ecosystems), Ozone Processes, Heat Stress and Drought, Acute Toxic Pollution Releases, Air Pollution, Inland and coastal water quality (Health), Algal blooms and waterborne infectious diseases, Tropospheric ozone (Weather), Tropospheric aerosol characterization (Water)
ACE	>2020	JAXA?	UV-Vis-SWIR wide swath measurements of: water-leaving radiance (ocean color radiometry), phytoplankton chl a, carbon stocks and ocean carbon uptake; ocean ecosystems, plankton physiology; aerosol and cloud optical depth; some aerosol and cloud properties via spectral and polarimetric observations; Radar and Lidar measurements of vertical profiles of aerosol and cloud properties; high accuracy and precision spectral and polarimetric measurements of aerosol and cloud properties; IR measurements of cloud properties; microwave measurements of water	Quantifying carbon budget (stocks, fluxes, monitoring and content in the ocean ecosystem); ecosystem health; plankton physiological status and climate impacts; ocean physical-biological interactions; land/sea carbon exchange, coastal water quality, HABs, and impact of natural and other hazards on ocean ecology; geographical distributions of cloud and aerosol properties; Aerosol/cloud interactions; 3 dimensional distributions of aerosol and cloud properties; aerosol and cloud radiative forcing of climate and weather; aerosol influence on precipitation and water cycle	Aerosol, cloud, and water radiative forcing (Climate); aerosol-cloud-precipitation interactions (Climate & Weather); atmospheric pollutant sources, transport and removal (Health); Carbon in the ocean ecosystem (Climate); global ocean productivity (Ecosystems); HABs (Health)

Appendix D: Abbreviations and Acronyms

ACE	Aerosols, Clouds and Ecosystem mission
AO	Announcement of Opportunity
AOURD	Accelerating Operational Use of Research Data
APS	Aerosol Polarimeter Sensor
ASCENDS	Active Sensing of CO_2 Emissions over Nights, Days and Seasons
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CDR	Critical Design Review
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CNES	French Space Agency (Centre National d'Etudes Spatiale)
CH_4	Methane
CO_2	Carbon dioxide
DESDynI	Deformation, Ecosystem Structure, and Dynamics of Ice
DLR	German Aerospace Center {Deutsches Zentrum fur Luft- und Rahmfahrt]
DPAF	Dual Payload Attach Fitting
DSS	Dual Spacecraft System
ELV	Expendable Launch Vehicle
EELV	Evolved Expendable Launch Vehicle
EPA	Environmental Protection Agency
E/PO	Education and Public Outreach
EOS	Earth Observing System
EOSDIS	EOS Data and Information System
ERBS	Earth Radiation Budget Satellite
ESA	European Space Agency
ESSP	Earth System Science Pathfinder
ESTO	Earth Science Technology Office
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FY	Fiscal Year
GACM	Global Atmosphere Composition Mission
GEO-CAPE	Geostationary Coastal and Air Pollution Events mission
GEOSS	Global Earth Observation System of Systems
GLOBE	Global Learning and Observations for a Better Environment
GMAO	Global Modeling and Assessment Office
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GPSRO	GPS Radio Occultation mission
GRACE	Gravity Recovery and Climate Experiment
HysplRI	Hyperspectral Infrared Imager
IDS	Interdisciplinary Science
IIP	Instrument Incubator Program
IPCC	Intergovernmental Panel on Climate Change
ISRO	India Space Research Organization
ISS	International Space Station
JAXA	Japan Space Exploration Agency
JCSDA	Joint Center for Satellite Data Assimilation
KaRIn	Ka-band Interferometric SAR
LDCM	Landsat Data Continuity Mission
LEO	Low Earth Orbit
LIST	Lidar Surface Topography mission
MoO	Missions of Opportunity
MODIS	Moderate resolution Imaging Spectrometer
MO&DA	Mission Operations and Data Analysis
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRA	NASA Research Announcement
NRC	National Research Council
NSF	National Science Foundation
NWP	Numerical Weather Prediction
OCO	Orbiting Carbon Observatory
OES	Ocean Ecosystem Spectroradiometer
OMB	Office of Management and Budget
OMPS	Ozone Mapper and Profiler Suite
OSTM	Ocean Surface Topography Mission
OSTP	Office of Science and Technology Policy
PACE	Pre-Aerosols Carbon, and Ecosystems Mission
PATH	Precipitation and All-weather Temperature and Humidity mission
PI	Principal Investigator
POD	Precision Orbit Determination
OSTP	Office of Science and Technology Policy
R&A	Research & Analysis
ROSES	Research Opportunities in the Space and Earth Sciences

Appendix D Continued

RY$M	Real Year Dollars in Millions
SAGE-III	Stratospheric Aerosols and Gas Experiment – III
SAR	Synthetic Aperture Radar
SCLP	Snow and Cold Land Processes
SCRC	Student Climate Research Campaign
SERVIR	Spanish abbreviation for Regional Visualization and Monitoring System
SMD	Science Mission Directorate (NASA)
SMAP	Soil Moisture Active/Passive
SPoRT	Short-term Prediction Research and Transition
STEM	Science, Technology, Engineering and Mathematics
SWOT	Surface Water Ocean Topography
TIRS	Thermal Infrared Sensor
UNEP	United Nations Environment Program
USAID	United States Agency for International Development
USGCRP	United States Global Change Research Program
USGEO	United States Group on Earth Observation
WMO	World Meteorological Organization