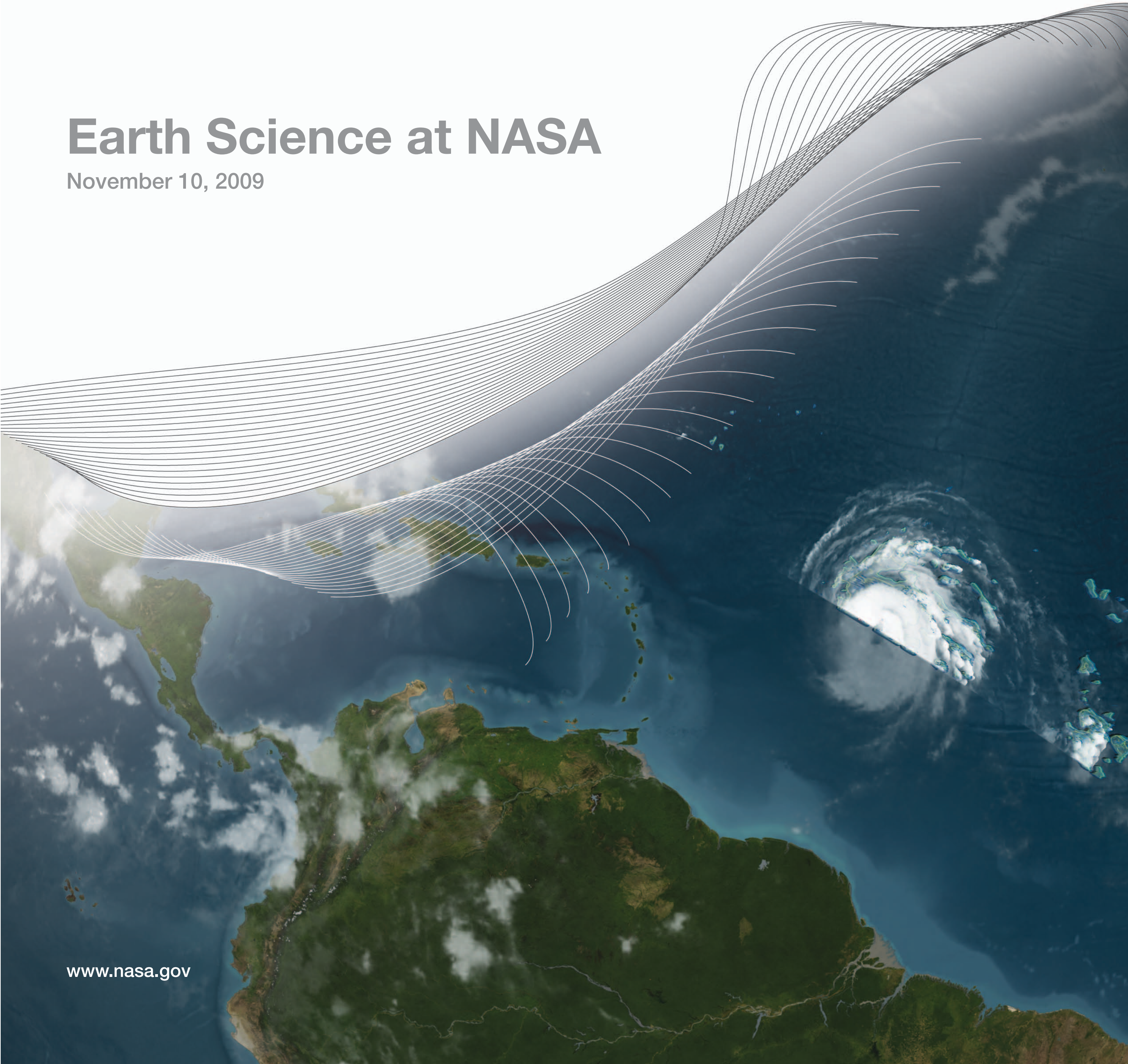
National Aeronautics and Space Administration

Earth Science at NASA

November 10, 2009



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EARTH SCIENCE AT NASA

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Introduction

The National Aeronautics and Space Administration (NASA) conducts a program of breakthrough research to advance fundamental knowledge on the most important scientific questions about the global integrated Earth system. NASA continues to lead the international scientific community to advance global integrated Earth system science using space-based observations. The research encompasses the global atmosphere; the global oceans including sea ice; land surfaces including snow and ice; ecosystems; and interactions among the atmosphere, oceans, land and ecosystems, including humans. NASA's goal is to understand the changing climate, its interaction with life, and how human activities affect the environment. Through partnerships with national and international agencies, NASA enables the application this understanding for the well-being of society. This document provides a describtive inventory of NASA's ressearch and observing activities in Earth system sceince, including climate science.

Much of the science community's present state of knowledge about global change—including many of the measurements and a significant fraction of the analyses which serve as the foundation for the assessment reports of the Intergovernmental Panel on Climate Change (IPCC) and the quadrennial ozone assessment by the World Meteorological Organization—are derived from NASA's Earth Science program. For example, using data from Earth observing satellites NASA-supported researchers are: discovering the abrupt rapidity of sea ice depletion in the Arctic cover and ice sheet motions in the Arctic and Antarctic; quantifying short-term and long-term changes to the Earth's protective shield of stratospheric ozone, including the positive impacts of the Montreal Protocol; developing robust relationships between increasing upper ocean temperature and decreasing primary production from the phytoplankton that form the base of the oceans' food chain; using a fleet of satellites flying in formation (the "A-Train") to study the effects of aerosols in the atmosphere on cloud formation and cloud cover; and using rainfall, vegetation, and other data to help predict food shortage conditions in developing countries. By flying satellites in formation through the A-Train, NASA is capable of making unique, global, near-simultaneous measurements of aerosols, clouds, temperature and relative humidity profiles, and radiative fluxes. Similarly, the use of satellites, aircraft, and ground-based monitoring stations provides NASA effectively calibration of new measuring capabilities and provides unprecedented views into numerous phenomenon, such as the origin of storms.

Our improved understanding of Earth System processes leads to improvements in sophisticated weather and climate models, which, in turn,—when initialized using the satellite data—can be used to predict natural and human-caused changes in the Earth's environment over time scales of hours to years.

NASA also makes strong investments in the development of new technologies that enable a range of scientific measurements, including those specified in the NRC's Decadal Survey, as well as make that data accessible for applications that benefit society. Technology funding now only supports the development of new sensors and instruments, but also advanced communications systems and computer modeling capabilities.

There is thus a strong synergy between our Nation's research satellites and our operational spaceborne systems. Near-real-time measurements from NASA research missions, such as the Tropical Rainfall Mapping Mission (TRMM), the Quick Scatterometer (QuikSCAT), and the Atmospheric Infrared Sounder instrument on the Aqua mission are used routinely by the National Oceanic and Atmospheric Administration (NOAA) and other U.S. and international agencies to improve weather forecasting. NASA works closely with NOAA and the other Federal agencies to transition satellite research measurement capabilities to long-term operations, as appropriate.

Inventory of Observing Capabilities

NASA presently has 15 satellite missions in orbit, as shown in Figure 1, each observing one or more aspects of Earth's climate system. Brief descriptions of NASA's current missions are provided in Table 1 and more detailed descriptions are provided in Appendix A.

On February 24, 2009, NASA's Orbiting Carbon Observatory (OCO) did not reach orbit altitude due to a launch vehicle failure.

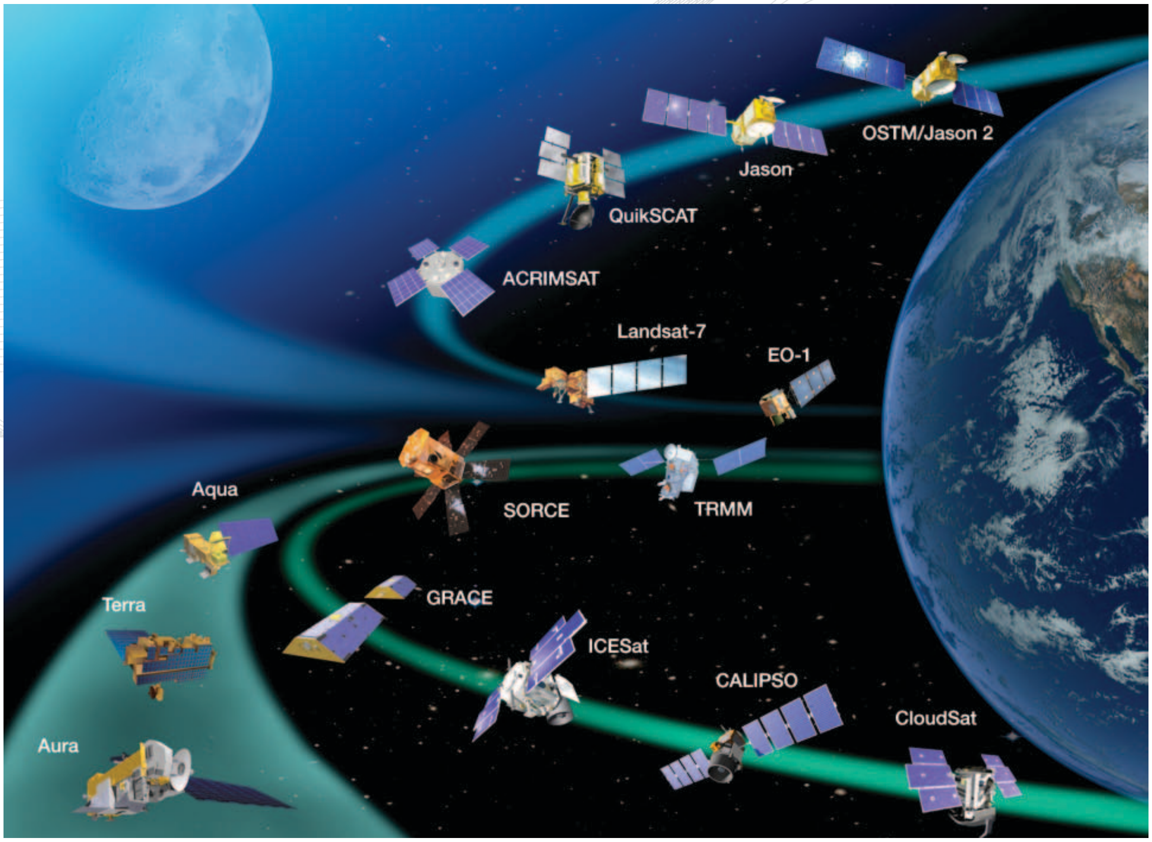


FIGURE 1
Currently operating NASA Earth Science missions that respond to the U.S. Global

Table 1 Brief descriptions of NASA's Earth Science missions currently in operation

Satellite	Launch Dates	Pricipal Measurement
ACRIMSAT	December 1999	Total solar irradiance
Aqua	May 2002	Atmospheric temperature & humidity
Aura	July 2004	Atmospheric composition
CALIPSO	April 2006	Clouds and aerosol properties
Cloudsat	April 2006	Cloud vertical structures
EO-1	November 2000	Land cover
GRACE	March 2002	Earth's gravity field
ICESat	January 2003	Ice sheet topography
Jason	December 2001	Ocean surface height
Landsat-7	April 1999	Land cover/land use change
OSTM/Jason-2	June 2008	Ocean surface height (successor for Jason)
QuikSCAT	June 1999	Ocean surface vector winds
SORCE	January 2003	Total solar irradiance (successor for ACRIMSAT)
Terra	December 1999	Multi-purpose land, ocean, atmosphere
TRMM	November 1997	Rainfall over the global tropics

NASA has five foundational missions in development for launch in 2010–2014, as shown in Figure 2. These missions were all planned prior to the 2007 NRC Earth Science Decadal Survey. Brief descriptions of these missions are provided in Table 2 and more detailed descriptions are provided in Appendix B.

The National Research Council's (NRC) Decadal Survey report "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" (NRC, 2007) is the principal determinant of the priorities of NASA's Earth Science satellite missions beyond those

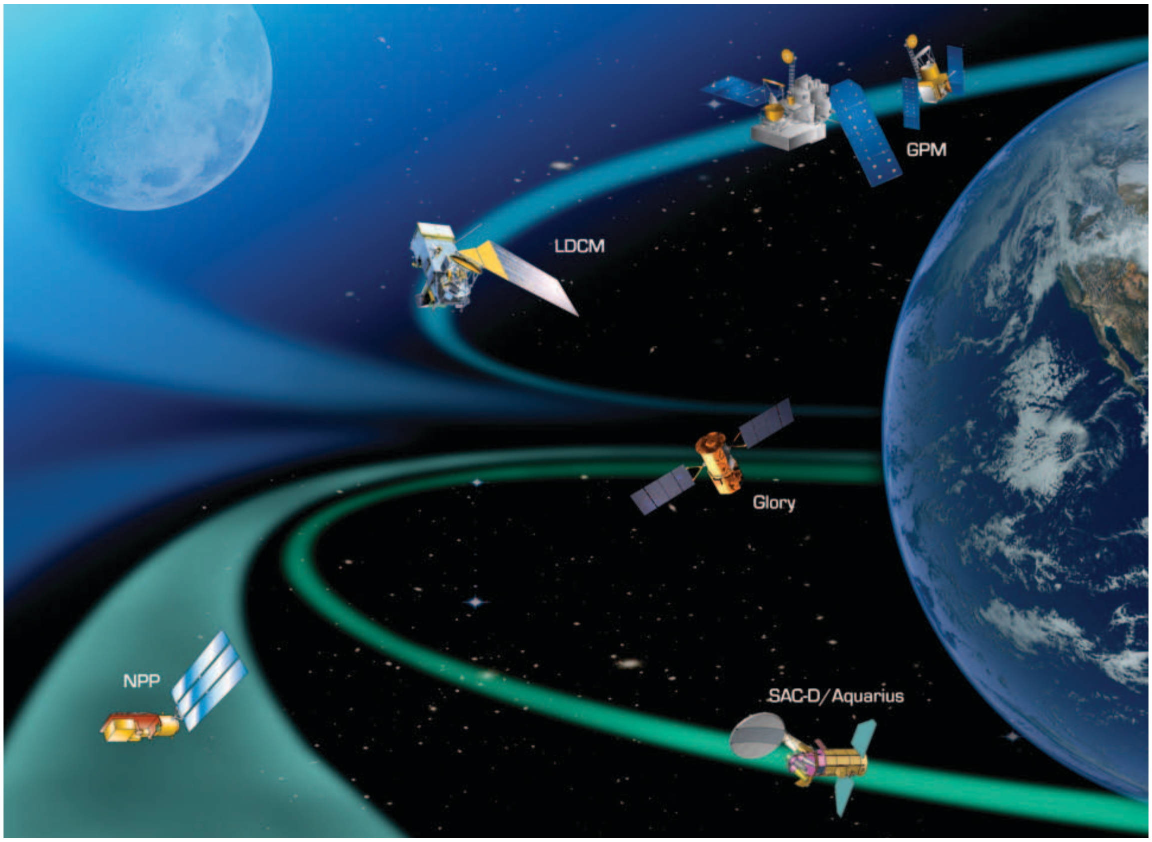


FIGURE 2
NASA Earth Science foundational missions under development.

Table 2 Brief descriptions of NASA Earth Science foundational missions currently in development

Satellite	Launch Dates	Pricipal Measurement
Aquarius	May 2010	Sea surface salinity
Glory	Late 2010	Aerosol properties & total solar irradianc
NPP	NET Jan 2011	Continue key measurements from Terra & Aqua
LDCM	Dec 2012	Land cover / land use change
GPM	2013	Global precipitation

currently in development. The NRC Decadal Survey recommended an integrated slate of missions in three sets (or Tiers, as NASA has come to call them), as shown in Figure 3.

Of the four Tier 1 missions, the Soil Moisture Active-Passive (SMAP) is in Phase A formulation and concept development study and the Ice, Cloud, and land Elevation Satellite (ICESat II) mission is expected to begin Phase A in FY 2010. The other two Tier 1 missions, Climate Absolute Radiance and Refractivity Observatory (CLARREO) and Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI), are currently the subject of engineering studies to prepare them to enter the formal mission formulation process. Detailed descriptions of these missions are provided in Appendix C.

In addition, the NRC Decadal Survey recommend NASA implement a new Venture class line of small, innovative research and applications missions. This class can be implemented as sub-orbital missions (e.g. on Unmanned Aerial Vehicles), instruments on other platforms, or dedicated small satellite missions. The first solicitation for Venture class missions was issued in July 2009.

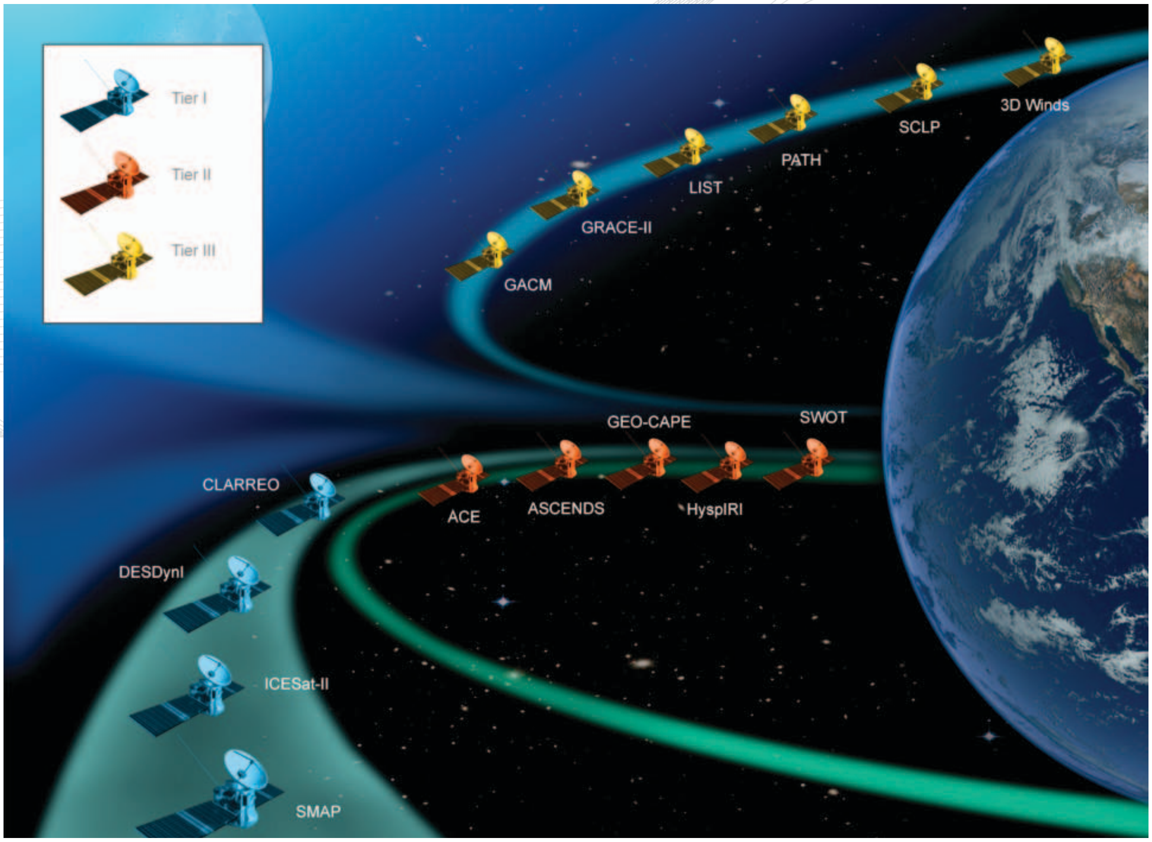


FIGURE 3
NRC Decadal Survey Missions, arranged by Tiers.

NASA aircraft- and surface-based instruments are used to calibrate and enhance interpretation of high-accuracy, climate-quality, stable satellite measurements. NASA, in recording approximately 4 terabytes of data every day, maintains the world's largest scientific data and information system for collecting, processing, archiving, and distributing Earth system data to worldwide users. NASA supports state-of-the-art computing capability and capacity for extensive global integrated Earth system modeling using satellite observations.

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

Ground networks help provide global, in situ measurements of important climate parameters through partnerships between NASA and other institutions around the world. For example, as the AErosol RObotic NETwork (AERONET) program provides globally distributed observations of aerosols in order to measure how much sunlight reaches the ground.

Through NASA's twelve Distributed Active Archive Centers (DAAC's), Earth Science data from these different sources are processed, archived, documented, and distributed to researchers and the general public. Each DAAC specializes in specific science disciplines in order to better support that community. Complete information on the DAAC's is available at: http://nasadaacs.eos.nasa.gov/index.html.

Inventory of Research Programs

Consistent with the goals of the U.S. Global Change Research Program, NASA pursues climate research activities focused on key areas of interaction in the climate system, specifically Atmospheric Composition, Climate Variability and Change, Water and Energy Cycles, Carbon Cycle and Ecosystems, Weather, Earth Surface and Interior, Modeling Strategy, Decision Support Resources Development, Observing and Monitoring the Climate System, and Data Management and Information.

Research Area: Atmospheric Composition

Atmospheric Composition studies changes in the Earth's atmospheric chemistry and composition, which determine air quality and affects weather, climate, and critical constituents such as ozone and carbon dioxide. Research in this area is geared toward creating a better understanding of changes in atmospheric composition and the time scales over which they occur, the forcings (man-made and natural) that drive the changes, the reaction of trace components in the atmosphere to global environment change and the resulting effects on the climate, the effects of global atmospheric chemical and climate changes, and air quality. NASA's research for furthering our understanding of atmospheric composition will provide an improved prognostic capability for issues such as the recovery of stratospheric ozone and its impacts of surface ultraviolet radiation, the evolution of greenhouse gases and their impacts on climate, and the evolution of tropospheric ozone and aerosols and their impacts on climate and air quality.

Figure 4 Research Highlight: Predicting Ozone Loss in the Arctic in development

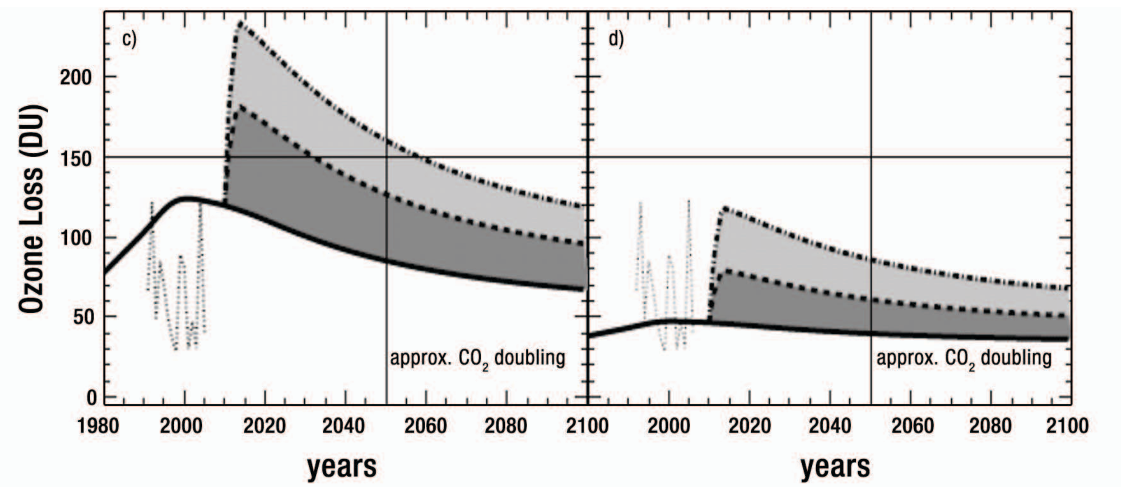


Figure 4. Researchers have projected the chemical loss over time of column ozone in the Arctic, for a base case (solid line) and two scenarios of climate geoengineering by the injection of stratospheric sulfate aerosols (dashed and dash-dot lines), for very cold (left) and moderately cold (right) conditions in the Arctic stratosphere during winter. The very cold conditions are similar to lower stratospheric temperatures during the Arctic winter of 2005, while the moderately cold conditions approximate lower stratospheric temperatures during the Arctic winter of 2003. These results demonstrate that severe loss of ozone could result from geoengineering of climate by the injection of sulfate aerosols into the stratosphere. The geoengineering scenarios represent different but plausible estimates of the amount and size of sulfate aerosols necessary to counter the surface warming that is likely to result from a doubling of atmospheric carbon dioxide. The projections are based on empirical relationships between ozone loss and stratospheric sulfate aerosol levels derived from measurements. The dotted lines in the left and right panels show the ozone loss estimated from the empirical relationship and observed sulfate loading and chlorine levels. These empirical relationships were derived almost entirely from data acquired by NASA satellites and aircraft, without which the projections would not have been possible. Data from the Halogen Occultation (HALOE) instrument, which flew on board the NASA Upper Atmosphere Research Satellite (1991–2004), was used to define the amount of chemical ozone loss that occurred during each Arctic and Antarctic winter. Concurrent data from the NASA Stratospheric Aerosol and Gas Experiment II (SAGE II) on board the Earth Radiation Budget Satellite (1984–2005) were used to develop the relationship between chemical ozone loss and the potential for chlorine activation, which is very sensitive to the amount of sulfate aerosol loading of the stratosphere. Measurements from the NASA Airborne Arctic Stratospheric Expedition II (October, 1991–March, 1992) campaign were also used to corroborate the satellite measurement-based relationships used in the study. (Tilmes, S., R. Muller, and R. Salawitch, The sensitivity of polar ozone depletion to proposed geoengineering schemes, Science, 320, 1201, 2008.)

Research Area: Climate Variability and Change

A unique NASA contribution to climate science is the frequent near-global coverage of observations from space of many properties of the integrated Earth system, including ice sheets, sea ice, sea level, clouds, snow cover, solar radiation, and humidity. NASA's role in characterizing, understanding and predicting climate variability and change is centered around providing the global scale observational data sets on the higher-inertia components of the climate system (oceans and ice), their forcings, and the interactions with the entire Earth system. Understanding these interactions goes beyond observations, to include the development and maintenance of modeling capabilities that allows for the effective use, interpretation, and application of the data. The ultimate objective is to enable predictions of change in climate on time scales ranging from seasonal to multi-decadal. As NASA pioneers new satellite measurements to enable this capability, we work with our agency partners to transition our demonstrated observational capabilities to operational capabilities run by other agencies.

Climate Change and Variability Research Highlight: ICESat Tracks Changes in Ice Cover and Ice Type in the Arctic

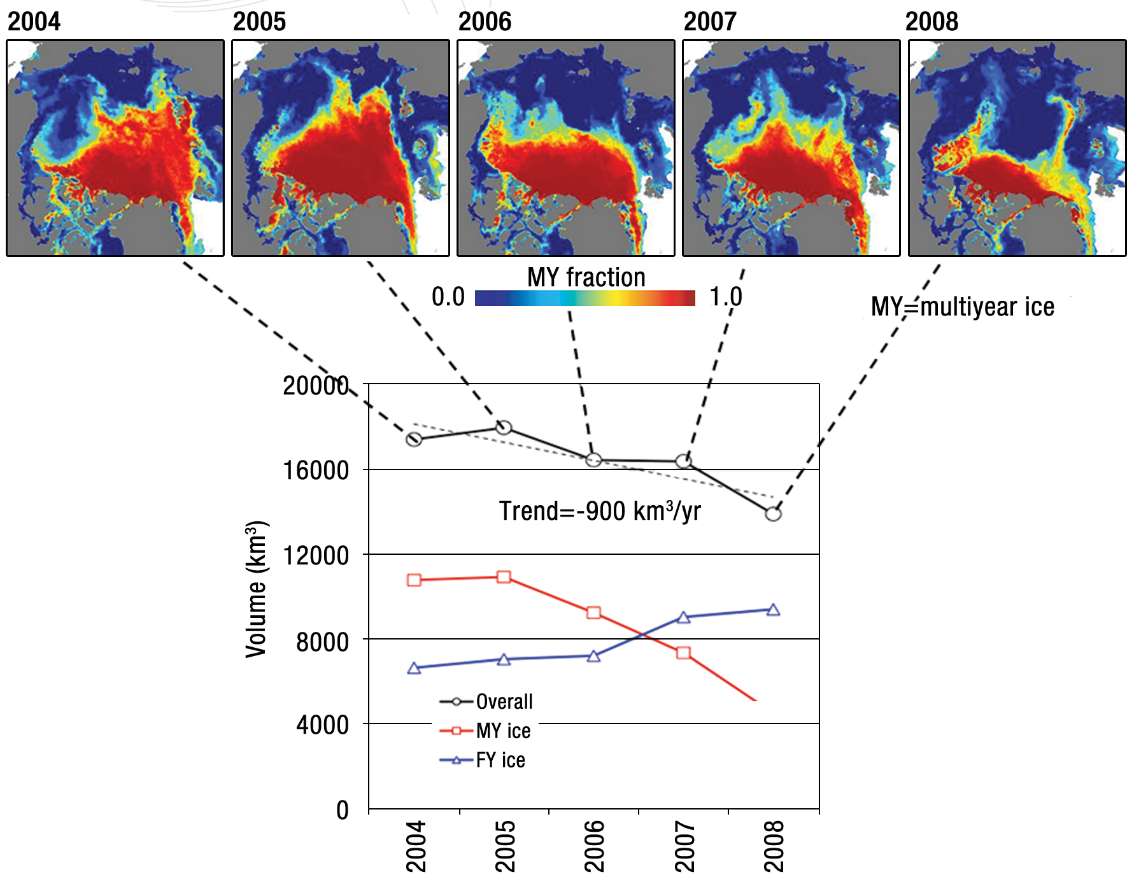


Figure 5. Using NASA's Ice, Cloud and land Elevation Satellite, known as ICESat, scientists have made the first basin-wide estimate of the thickness and volume of the Arctic Ocean's ice cover. The new results provide further evidence for the rapid, ongoing transformation of the Arctic's ice cover as Arctic sea ice thinned dramatically between the winters of 2004 and 2008, with thin seasonal ice replacing thick older ice as the dominant type for the first time on record. During the study period, the relative contributions of the two ice types to the total volume of the Arctic's ice cover were reversed. In 2003, 62 percent of the Arctic's total ice volume was stored in multi-year ice, with 38 percent stored in first-year seasonal ice. By 2008, 68 percent of the total ice volume was first-year ice, with 32 percent multi-year. The research team attributes the changes in the overall thickness and volume of Arctic Ocean sea ice to the recent warming and anomalies in patterns of sea ice circulation. (Kwok, R., and G. F. Cunningham (2008), ICESat over Arctic sea ice: Estimation of snow depth and ice thickness, J. Geophys. Res., 113, C08010, doi:10.1029/2008JC004753.)

Research Area: Water and Energy Cycles

The Water and Energy Cycle Focus Area studies the distribution, transport and transformation of water and energy within the Earth System. The water cycle involves water in all three of its phases, including clouds and precipitation; ocean-atmosphere, cryosphere-atmosphere, and land-atmosphere interactions; mountain snow; and groundwater. Since solar energy drives the water cycle and energy exchanges are modulated by the interaction of water with radiation, the energy cycle and the water cycle are intimately entwined. The long-term goal of this focus area is to enable improved predictions of the global water and energy cycles. This key goal requires not only documenting and predicting means and trends in the rate of the Earth's water and energy cycling as well as predicting changes in the frequency and intensity of related meteorological and hydrologic events such as floods and droughts.

Water and Energy Cycles Research Highlight: GRACE Calculates Groundwater Depletion Rates in India

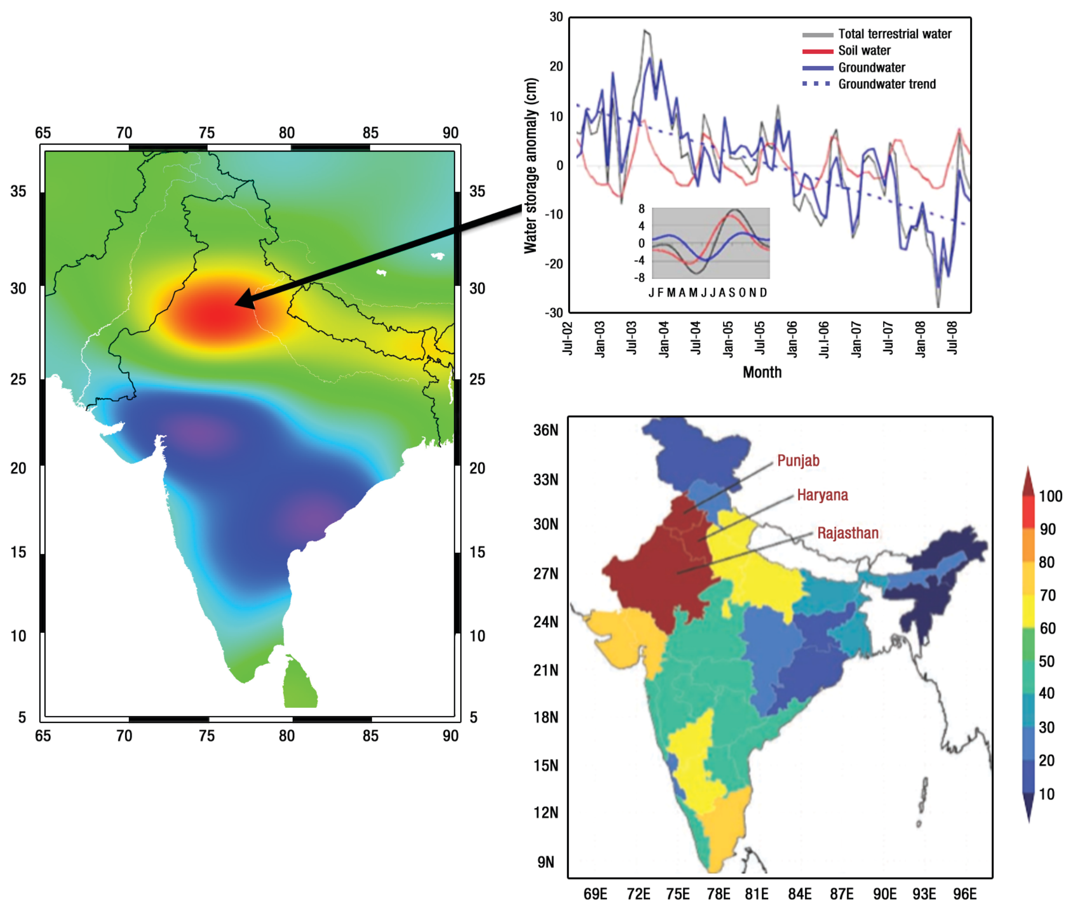
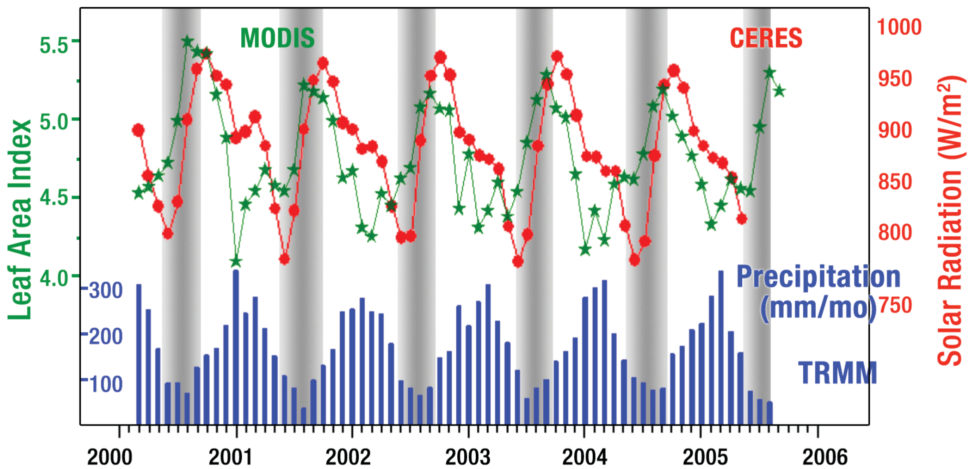


Figure 6. Gravity Recovery and Climate Experiment (GRACE) data can be used to track groundwater depletion rates over regional scales. The map shows the rate of change of groundwater storage in India during 2002–≠08, with losses shown in deepening shades of red and gains in blue. The estimated rate of depletion of groundwater in northwestern India (averaged over the states of Rajasthan, Punjab, and Haryana, which includes the national capital of New Delhi) is 4.0 centimeters of water per year, equivalent to a water table decline of about 33 centimeters per year. Increases in groundwater in southern India are due to greater than normal rainfall in the past few years, whereas northwestern India received close to normal rainfall throughout the study period. (M. Rodell et al. Nature doi:10.1038/nature08238; 2009)

Research Area: Carbon Cycle and Ecosystems

The Carbon Cycle and Ecosystems Focus Area addresses the distribution and cycling of carbon among the land, ocean, and atmospheric reservoirs and ecosystems as they are affected by humans, as they change due to their own biogeochemistry, and as they interact with climate variations. Through a series of direct measurements and models, NASA helps to characterize and quantify greenhouse gases and related controlling processes in the terrestrial, near-surface aquatic, and atmospheric environments. Given the importance of understanding how carbon cycles through the environment, NASA maintains a vigorous research program to study the distribution and the forces determining the atmospheric concentrations of carbon dioxide and other key carbon-containing atmospheric gases (especially methane), as well as carbon-containing aerosols. NASA improves understanding of the structure and function of global marine and terrestrial ecosystems, their interactions with the atmosphere and hydrosphere, and their role in cycling biogeochemical elements.

Carbon and Ecosystems Research Highlight: NASA Satellites Show Unexpected Seasonal Growing



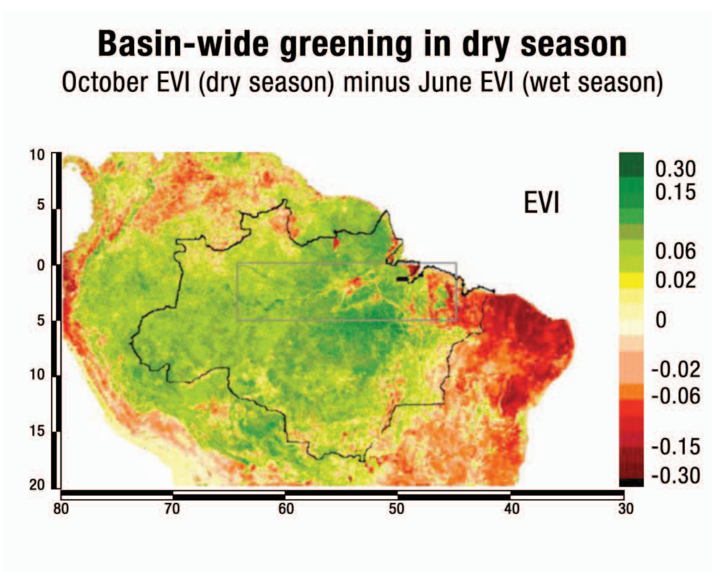


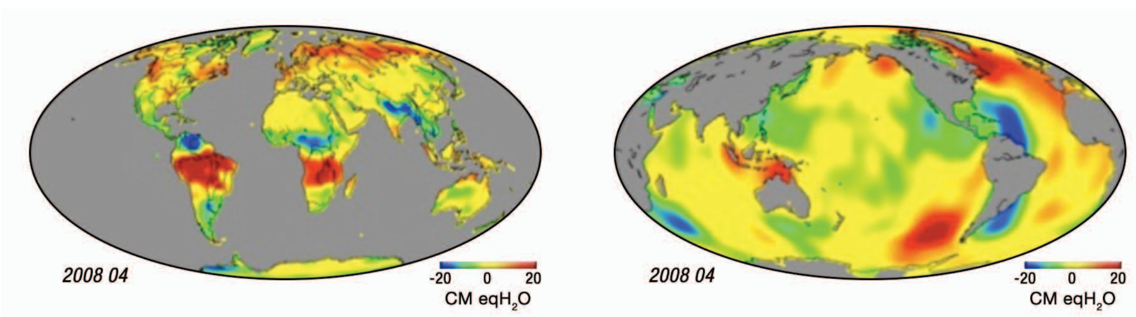
Figure 7. Two research teams studying the Amazon Rain Forest from space have demonstrated fundamentally new understanding of the seasonality of rain forest ecosystems. In one study (above), measurements of leaf area index from MODIS on Terra, precipitation from TRMM, and solar radiation from CERES (also on Terra), show that leaf area is high when solar radiation is high and low when rainfall (and cloudiness) is high. This shows that the productivity of these tropical forests is light limited, not water limited. (Myneni, et al. Large seasonal swings in leaf area of Amazon rainforests. PNAS 2007 104:4820-4823; doi:10.1073/pnas.06113381042007.) In the second study (left), MODIS was used to show that seasonal patterns of forest productivity in the Amazon are opposite to what had been previously understood; the forests are more productive in the dry season when more light is available. They concluded that the forest trees are able to tap deep soil water and avoid the water limitations that pastures in the region experience during the short dry season. (Huete, et al. (2006), Amazon rainforests green-up with sunlight in dry season, Geophys. Res. Lett., 33, L06405, doi:10.1029/2005GL025583.)

Research Focus Area: Earth Surface and Interior

The goal of the Earth Surface and Interior focus areas is to assess, mitigate, and forecast the natural hazards through a better understanding of the transport of mass and energy within the Earth System. The Earth's surface and its interior are fundamental components of the Earth system that both influence and react to the dynamics of our oceans and atmosphere. Therefore, an understanding the dynamics of the solid Earth is essential to developing an interconnected view of Earth science and its applications that ranges from natural hazards and climate change to fundamental physics. Space geodetic science and its associated geodetic ground networks and satellite missions such as GRACE, LAGEOS, and soon DESDynI provide the measurements to monitor crustal deformation, sea level change, water storage, ice dynamics and ablation and numerous other influences from the transport of mass and energy through the Earth System. Though these topics are very interdisciplinary in nature, the Earth Surface and Interior Focus Area provides the primary support for the development of Space Geodetic science and associated missions and infrastructure.

Earth Surface and Interior Research Highlight: Monthly Assessments of Earth's Gravity Field

Figure 8. NASA's Gravity Recovery and Climate Experiment (GRACE) provides monthly to semi-monthly estimates of variations in the Earth's gravity field with unprecedented accuracy and precision. This figure shows the Earth's gravity field in April 2008 for land variations (left) and ocean variations (right). Land gravity field variations are stronger than those for the ocean. Such monitoring capabilities are essential for understanding seasonal anomalies and other variations in the Earth's gravity field. GRACE itself depends upon NASA's space geodetic networks for its precise positioning requirements.



Research Focus Area: Weather

Our weather system includes the dynamics of the atmosphere and its interactions with the oceans and land. The Weather focus area is important to the NASA Earth Science for two reasons. First, the improvement of our understanding of weather processes and phenomena is crucial in gaining an understanding of the Earth system. It is directly related to the Climate and Water/Energy Cycle focus areas. In both cases, the dynamics are to a large degree controlled by "weather processes." Second, there is an infrastructure in the U.S. for operational meteorology at NOAA, the FAA, the DoD, and others that requires the introduction of new technologies and knowledge that only NASA can develop.

Weather Research Highlight: AIRS Data Improves Hurricane Forecasting for Cyclone Nargis

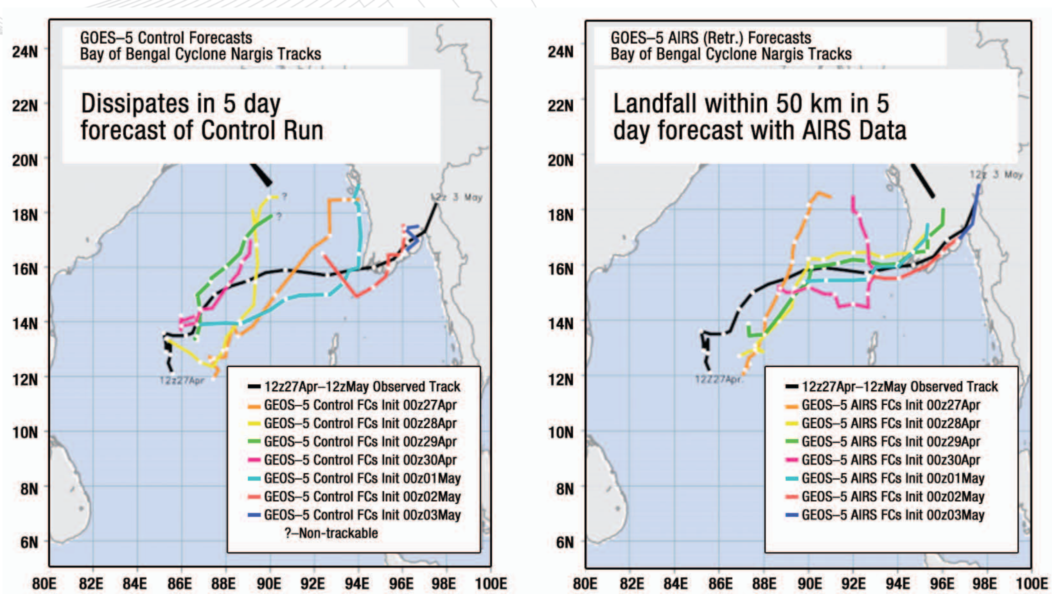


Figure 9. Recent studies using NASA's Atmospheric Infrared Sounder (AIRS) on the Aqua spacecraft have demonstrated the tremendous value of hyper-spectral infrared observations to improving weather forecast. In a study performed by scientists at NASA's Goddard Space Flight Center (GSFC), AIRS temperature profiles were assimilated into the GEOS-5 forecasting system to evaluate the forecast improvement of tropical cyclone Nargis that caused the worst natural disaster in the history of Burma. The 5 day forecast control run without AIRS data (left) showed the cyclone dissipating prior to landfall in a position 200 km north of the actual track. After assimilation of AIRS cloud-cleared temperature profiles the cyclone produced an accurate track in 5 of the 7 runs during the forecast period (right). In fact, in the 108 hour forecast, the displacement error at landfall time is less than 50 km with the coordinates of the storm at that time 16.44°N, 94.7°E in the AIRS run, against the observed of 16.00°N, 94.7°E in the actual position recorded. (Reale, O., W. K. Lau, J. Susskind, E. Brin, E. Liu, L. P. Riishojgaard, M. Fuentes, and R. Rosenberg (2009), AIRS impact on the analysis and forecast track of tropical cyclone Nargis in a global data assimilation and forecasting system, Geophys. Res. Lett., 36, L06812, doi:10.1029/2008GL037122.)

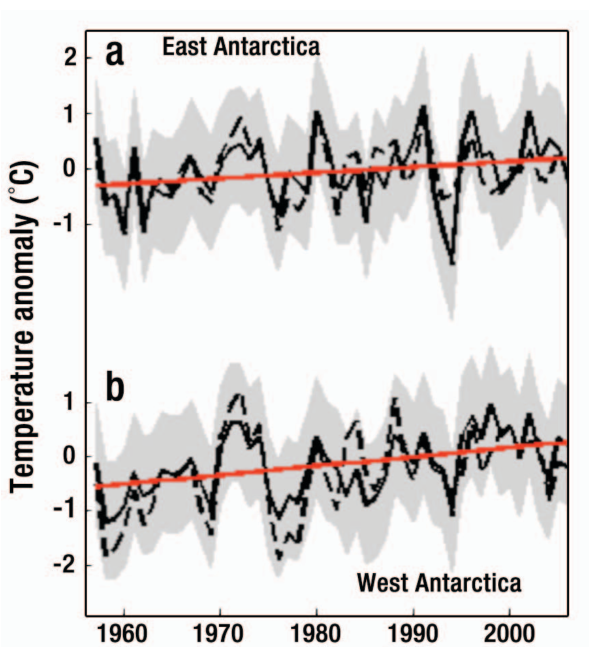
Disciplinary and Interdisciplinary Research Programs

Underlying the Science Focus Areas that explore key climate and Earth system interactions are a core set of foundational Earth science disciplinary and interdisciplinary research programs. These are primarily comprise competitively-selected research grants issued in response to NASA Research Announcements, particularly the annual omnibus Research Opportunities in Space and Earth Sciences (ROSES). These programs include:

- Cryospheric science
- Land use/land cover change
- Ocean biology and biogeochemistry
- Terrestrial ecology
- Physical oceanography
- Terrestrial hydrology
- Precipitation science
- Atmospheric modeling and analysis
- Interdisciplinary research in Earth science

On average, NASA sponsors 1100 research grants and thousands of researchers in universities and industrial and government labs around the nation conducting Earth Science research.

Quantitative understanding of Earth system processes and feedbacks is codified in climate models. The Earth System Modeling Framework—which was initiated in 2002 by NASA and now is an interagency activity—enables shared infrastructure and interoperability of model components and interface.

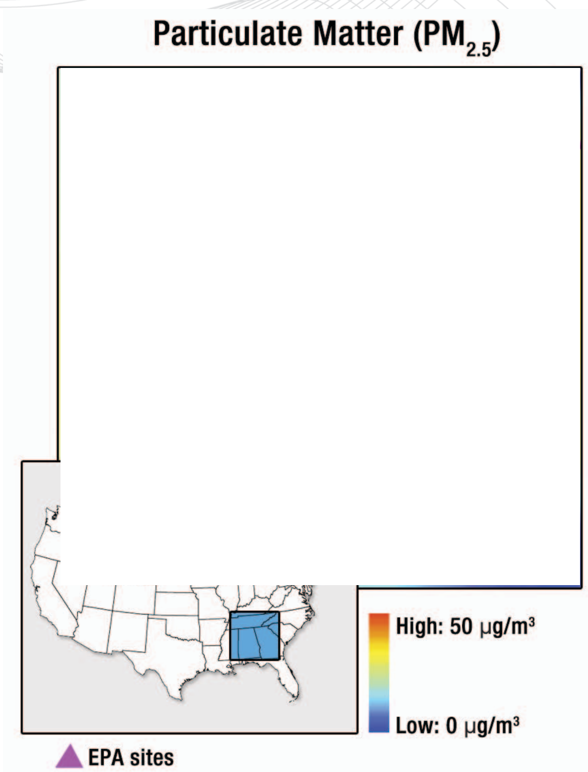


Interdisciplinary Research Highlight:
Unexpected Warming in Antarctica

Fundamental work shows that East Antarctica—long thought to be cooling—is warming. Reconstructed temperatures using Advanced Very High Resolution Radiometer (AVHRR) and station data shows a warming trend of 0.1oC per decade overall in Antarctica but with a stronger warming trend of 0.2oC per decade in West Antarctica. (Steig, E.J., D.P. Schneider, S.D. Rutherford, M.E. Mann, J.C. Comiso and D. T. Shindell (2009) Warming of the Antarctic ice sheet surface since the 1957 International Geophysical Year, Nature, 457, 459-463.)

Applied Sciences

NASA develops and demonstrates practicable applications of its research satellite observations and model results for use by decision makers. NASA works directly with decision makers throughout the development of applications. Examples include improved public health tracking systems for deadly diseases with the Center for Disease Control; advances in prediction of weather conditions for airplane pilots through the National Weather Service and the Federal Aviation Administration; improved tracking of air pollutants with the Environmental Protection Agency for decision-making on biomass burning and industrial practices; improving the Department of Agriculture's Global Economic Forecasting; and providing tools for better disaster management by state and local first responders.

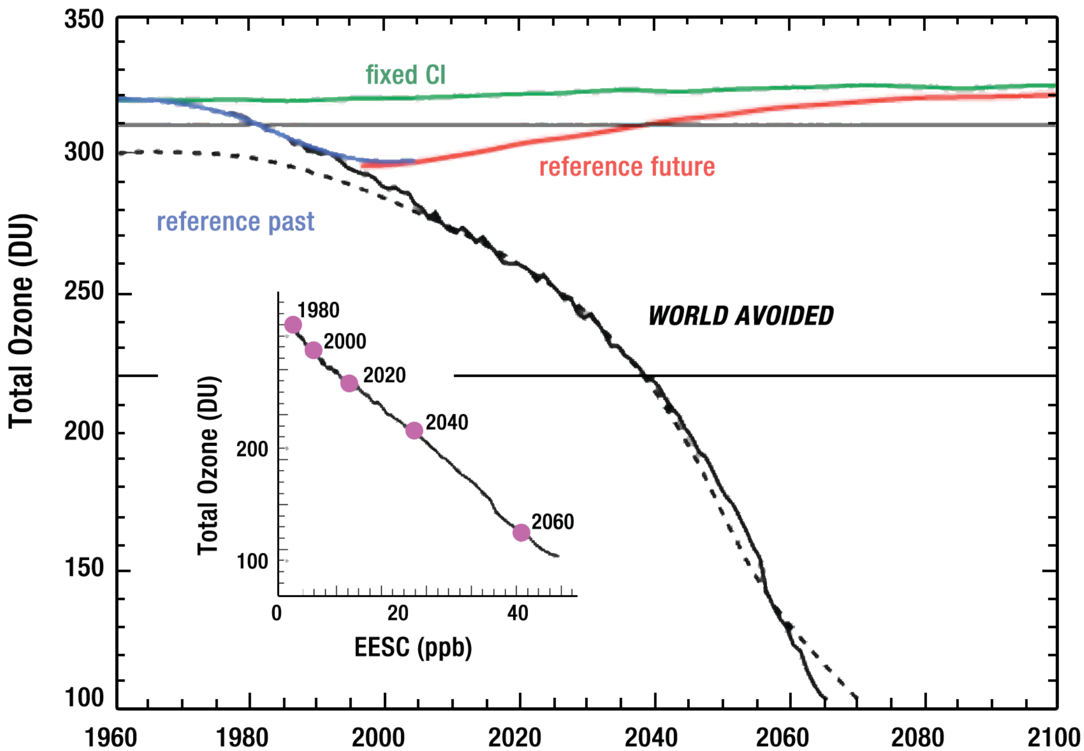


Applied Sciences Research Highlight: NASA and CDC Partner to Provide Improved Public Health Tracking

Accurately monitoring concentrations of 2.5 micron particulate mater ($PM_{2.5}$) are difficult using ground observations alone. Similarly, 10 micron PM (from naturally occurring dust) are associated with asthma and other respiratory distress in the desert Southwest. NASA and the CDC have been partners in linking $PM_{2.5}$ and PM10 and health observations to enhance public health surveillance through the CDC Environmental Public Health Tracking Network (EPHTN). The EPHTN, a surveillance tool that scientists, health professionals, and—for the first time—members of the public can use to track environmental exposures and chronic health conditions, went operational in July 2009. NASA was an integral partner in enhancing the capabilities of this system as it was developed, using surfacing algorithms, modeling capabilities, and observations FROM A VARIETY OF NASA EARTH SCIENCE SATELLITES AND SENSORS INCLUDING MODIS, ABOARD THE NASA TERRA AND AQUA SATELLITES. (The Application of Satellite Derived Environmental Data to Improve Environmental Public Health Surveillance Systems. NASA Tech. Report, 2006.; Al-Hamdan, et al.; and Niskar, A. 2009. "Methods for Characterizing Fine Particulate Matter Using Ground Observations and Remotely Sensed Data: Potential Use for Environmental Public Health Surveillance. Journal of the Air & Waste Management Association". 59:865–881.)

Information Useful to Policy Makers

The climate science data and results produced by NASA's Earth Science program have broad applicability beyond research, including the provision of a scientific basis for policy concern and policy choices. NASA observations are the principal source of global observations for the U.S. Global Change Research Program, and NASA observations and research provided a substantial portion of the input to the scientific assessments of the Intergovernmental Panel on Climate Change (IPCC), which are created for policy purposes. In addition, NASA partners with the World Meteorological Organization to produce a triennial assessment of the health of the Earth's stratospheric ozone layer, which shields the surface from harmful ultraviolet radiation.



Policy Highlight: NASA Researchers Evaluate Impacts of the Montreal Protocol

Figure 12. A team of NASA scientists have simulated "what might have been" if chlorofluorocarbons (CFCs) and similar chemicals were not banned through the Montreal Protocol. CFCs are known to deplete ozone in the atmosphere, which results in an increase in ultraviolet radiation reaching the surface of the Earth. The simulation used a comprehensive model that included atmospheric chemical effects, wind changes, and radiation changes. Annual average concentrations of global ozone are shown for the "World Avoided" (solid black), a modeled future with ozone regulation (red), atmospheric chlorine at a fixed amount (green), and a simulation of past observations (blue). The inset shows how ozone concentrations decrease as the amount of chlorine in the atmosphere—effective equivalent stratospheric chlorine (EESC)—grows over time. The simulation has shown that, without regulation, by 2065, 67% of the overhead ozone would be destroyed in comparison to 1980. Large ozone depletions in the polar region would become year-round rather than just seasonal, as is currently observed in the Antarctic ozone hole. Ozone levels in the tropical lower stratosphere remain constant until about 2053 and then collapse to near zero by 2058 as a result of "polar ozone hole" chemical processes developing in the tropics. In response to ozone changes, ultraviolet (UV) radiation increases, tripling the "sun-burning" radiation in the northern summer mid-latitudes by 2065. (Newman et al. What would have happened to the ozone layer if chlorofluorocarbons (CFCs) had not been regulated?, Atmospheric Chemistry and Physics, 9, 2113-2128, 2009)

Policy makers, of course, ultimately determine what is of most use to them. But recent experience points to the following as examples of observing data and research results capturing policy makers' attention:

- Global average temperature records and regional variations
- Weather forecasting, including tracking extreme weather events
- Relative strengths of climate "forcings" (especially the ability to distinguish natural from anthropogenic causes of climate change, e.g., by measuring solar irradiance)
- Sea-level rising faster than expected
- Sea-ice extent (especially rapid decline in Arctic summer sea ice extent in recent years)
- Greenland and Antarctica ice mass, especially ice shelf collapse in the Antarctic peninsula
- Inter-regional and intercontinental transport of air pollution
- Precipitation and drought patterns
- Rates of deforestation/reforestation and urbanization
- Stratospheric ozone recovery, and the impact of climate change on rate of recovery
- Carbon sources and sinks.

Sufficiency of Observing Activities Over the Next 5–7 Years

NASA's Earth Science program conducts observation and research programs to answer climate and Earth system science questions formulated through engagement with the science community. Observing activities are planned to optimize progress on these questions within the available resources. The Nation has other Earth observation needs in areas such as weather forecasting and natural hazard management, to which NASA observing missions and research can contribute, along with those of other agencies. This results in collaborative programs such as the Landsat series and NPOESS. Thus, while NASA can address sufficiency from the standpoint of its research goals, other agencies are better positioned to address sufficiency of observing activities for their needs.

Some science questions require research satellite measurements longer than the normal operating period of a satellite mission. The NASA strategy for long-term data acquisition has two facets. On some occasions, NASA will re-fly a proven satellite instrument measurement capability. An example in the attachment is the Clouds and the Earth's Radiant Energy System (CERES) instrument for measurement of total solar irradiance at the top of the atmosphere. On other occasions, NASA works with operational agencies like NOAA to continue a satellite measurement capability that NASA developed and tested. The tables in Appendix D show the measurements obtained through currently operational missions and display NASA's current research missions (Table 3) and identify what planned foundational missions (Table 4) and future Decadal Survey missions (Table 5) would continue those measurements.

As shown in the table below, NASA transferred to NOAA the operational control of health and safety of the Ocean Surface Topography Mission (OSTM) satellite, which was launched by NASA. The OSTM nadir sea surface topography measurement capability is sustaining the high accuracy global sea level data produced by NASA's TOPEX/Poseidon (August 1992–October 2005) and Jason (December 2001–present) missions. NOAA has become the U.S. lead for the OSTM follow-on mission called Jason-3.

Appendicies

Appendix A—NASA Earth Science Missions Currently In Operation

Active Cavity Radiometer Irradiance Monitor (ACRIMSAT)
Launch Date: December 20, 1999
Web Site: http://acrim.jpl.nasa.gov

ACRIMSAT, with its ACRIM III instrument, studies total solar irradiance from the Sun. It is theorized that as much as 25 percent of the Earth's total global warming may be solar in origin due to small increases in the Sun's total energy output since the last century. By measuring incoming solar radiation and adding measurements of ocean and atmosphere currents and temperatures, as well as surface temperatures, climatologists will be able to improve their predictions of climate and global warming over the next century. NASA has been measuring total solar irradiance via the ACRIM instrument since the launch of ACRIM I on the Solar Maximum Mission in 1980. The Upper Atmospheric Research Satellite (UARS), launched in 1991, flew ACRIM II.

Aqua
Launch Date: May 04, 2002
Home Page: http://aqua.nasa.gov

Aqua was launched with six state-of-the-art instruments to observe the Earth's oceans, atmosphere, land, ice and snow covers, and vegetation, providing high measurement accuracy, spatial detail, and temporal frequency. In particular, the Aqua data includes information on water vapor and clouds in the atmosphere, precipitation from the atmosphere, soil wetness on the land, glacial ice on the land, sea ice in the oceans, snow cover on both land and sea ice, and surface waters throughout the world's oceans, bays, and lakes. Such information helps scientists improve the quantification of the global water cycle and examine such issues as whether or not the cycling of water might be accelerating.

Aura
Launch Date: July 15, 2004
Web Site: http://aura.gsfc.nasa.gov

NASA's Aura mission seeks to understand and protect the air we breathe by making truly comprehensive measurements of the Earth's atmosphere. Aura's four instruments enable daily global observations of Earth's atmospheric ozone layer, air quality, and key climate parameters. Aura is able to monitor five of the six Environmental Protection Agency principle pollutants to be monitored: carbon monoxide, nitrogen dioxide, sulfur dioxide, ozone, and particulates (aerosols). Aura provides data of suitable accuracy to improve industrial emission inventories, and also to help distinguish between industrial and natural sources. Together, Aura's instruments provide global monitoring of air pollution on a daily basis.

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)
Launch Date: April 28, 2006
Home Page: http://www-calipso.larc.nasa.gov

The CALIPSO satellite helps scientists answer significant questions and provide new information about the effects of clouds and aerosols (airborne particles) on changes in the Earth's climate. Understanding the behavior of these components is essential for a better understanding of the Earth's climatic processes and improving the accuracy of climate model predictions used to make informed policy decisions about global climate change. CALIPSO measurements taken in conjunction with the Aqua satellite enable new observationally based assessments of the radiative effects of aerosol and clouds that will greatly improve our ability to predict future climate change. CALIPSO measurements taken in conjunction with CloudSat provide a thorough characterization of the structure and composition of clouds and their effects on climate under all weather conditions.

CloudSat
Launch Date: April 28, 2006
Web Site: http://cloudsat.atmos.colostate.edu

Unlike ground-based weather radars that use centimeter wavelengths to detect raindrop-sized particles, CloudSat's radar allows us to detect the much smaller particles of liquid water and ice that constitute the large cloud masses that make our weather. CloudSat's advanced radar "slices" through clouds to see their vertical structure, providing a completely new observational capability from space. Because clouds have such a large impact on Earth's radiation budget, even small changes in cloud abundance or distribution could alter the climate more than the anticipated changes in greenhouse gases, anthropogenic aerosols, or other factors associated with global change. Changes in climate that are caused by clouds may in turn give rise to changes in clouds due to climate: a cloud-climate feedback. These feedbacks may be positive (reinforcing the changes) or negative (tending to reduce the net change), depending on the processes involved. These considerations lead scientists to believe that the main uncertainties in climate model simulations are due to the difficulties in adequately representing clouds and their radiative properties.

New Millennium Program Earth Observing-1 (EO-1)
Launch Date: November 21, 2000
Web Site: http://eo1.gsfc.nasa.gov

EO-1 is an advanced land-imaging mission that demonstrates new instruments and spaccraft systems, which contribute to a significant reduction in cost of follow-on Landsat missions and other satellites. The EO-1 mission includes three advanced land imaging instruments and five revolutionary cross-cutting spacecraft technologies. EO-1 had a 1-year primary mission but was so successful that it continues to operate as a testbed for automated sensor web applications, and to collect unique hyperspectral data (more than 220 spectral colors) of the land surface, useful both for algorithm development and disaster response.

Gravity Recovery and Climate Experiment (GRACE)
Launch Date: March 17, 2002
Web Site: http://www.csr.utexas.edu/grace

The primary goal of the GRACE mission is to accurately map variations in the Earth's gravity field over its planned 5-year lifetime. The gravity variations that GRACE studies include: changes due to surface and deep currents in the ocean; runoff and ground water storage on land masses; exchanges between ice sheets or glaciers and the oceans; and variations of mass within the Earth. Another goal of the mission is to create a better profile of the Earth's atmosphere. The results from this mission yield crucial information about the distribution and flow of mass within the Earth and it's surroundings.

Ice, Clouds, and Land Elevation Satellite (ICESat)
Launch Date: January 12, 2003
Web Site: http://icesat.gsfc.nasa.gov

The primary goal of ICESat is to quantify ice sheet mass balance and understand how changes in the Earth's atmosphere and climate affect polar ice masses and global sea level. ICESat also measures the distribution of clouds and aerosols, as well as surveys land topography, sea ice, and global ice mapping. The ICESat mission provides multi-year elevation data needed to determine ice sheet mass balance as well as cloud property information, especially for stratospheric clouds common over polar areas. It also provides topography and vegetation data around the globe, in addition to the polar-specific coverage over the Greenland and Antarctic ice sheets. Future missions will extend and improve assessments from ICESat, as well as monitor ongoing changes.

Jason-1
Launch Date: December 07, 2001
Web Site: http://sealevel.jpl.nasa.gov/mission/jason-1.html

Jason is an oceanography mission to monitor global ocean circulation, improve global climate predictions, and monitor events such as El Niño conditions and ocean eddies. Earth's oceans are the greatest influence on global climate, yet only from space can we observe our vast oceans on a global scale and monitor critical changes in ocean currents and heat storage. Accurate observations of sea-surface height and ocean winds provide scientists with information about the speed and direction of ocean currents and about the heat stored in the ocean that, in turn, reveals global climate variations. Continuous altimetry data from satellites like Jason-1 help us understand and foresee the effects of the changing oceans on our climate and on climate events such as El Niño and La Niña. Jason-1 is a follow-on mission to the highly successful TOPEX/Posiedon mission (decommissioned in 2005) and precursor to OSTM/Jason 2 (launched in 2008).

Landsat 7
Launch Date: April 15, 1999
Web Site: http://landsat.gsfc.nasa.gov

The Landsat 7 Project is a joint initiative of the U.S. Geological Survey (USGS) and the NASA to gather Earth resource data, and is the most recent in a long series of Landsat satellites going back 30 years to 1974. Landsat 7 systematically provides well-calibrated, multispectral, moderate resolution, substantially cloud-free, Sun-lit digital images of the Earth's continental and coastal areas with global coverage on a seasonal basis. Landsat's Global Survey Mission is to establish and execute a data acquisition strategy that ensures repetitive acquisition of observations over the Earth's land mass, coastal boundaries, and coral reefs; and to ensure the data acquired are of maximum utility in supporting the scientific objectives of monitoring changes in the Earth's land surface and associated environment.

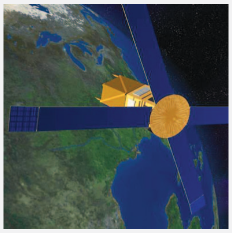
Ocean Surface Topography Mission (OSTM, Jason-2)
Launch Date: June 20, 2008
Web Site: http://sealevel.jpl.nasa.gov/mission/ostm.html

OSTM is an international effort to measure sea surface height by using a radar altimeter mounted on a low-Earth orbiting satellite called Jason-2 and is a follow-on to the Jason-1 and TOPEX/Poseidon missions. This satellite altimetry mission provides sea surface heights for determining ocean circulation, climate change and sea-level rise. The research satellites, TOPEX/Poseidon and Jason-1, have been instrumental in meeting NOAA's operational need for sea surface height measurements necessary for ocean modeling, forecasting El Niño/La Niña events, and hurricane intensity prediction. OSTM takes oceanographic studies of sea surface height into an operational mode for continued climate forecasting research and science and industrial applications.

Quick Scatterometer (QuikSCAT)
Launch Date: June 19, 1999
Web Site: http://winds.jpl.nasa.gov/missions/quikscat

QuikSCAT is the primary source of global ocean surface wind vectors and wind stress for science applications such as ocean and climate model forcing, air-sea interaction studies, and hurricane studies. QuikSCAT data are routinely assimilated in operational numerical weather prediction models at meteorological agencies worldwide, and have revolutionized the analysis and short-term forecasting of winds over the oceans. SeaWinds, the main instrument on QuikSCAT, measures near-surface wind speed and direction under all weather and cloud conditions over Earth's oceans. The instrument collects data over ocean, land, and ice in a continuous, 1,800-kilometer-wide band, making approximately 400,000 measurements and covering 90% of Earth's surface in one day. QuikSCAT can acquire hundreds of times more observations of surface wind velocity each day than can ships and buoys, and can provide continuous, accurate and high-resolution measurements of both wind speeds and direction regardless of weather conditions.

SeaWiFS
Launch Date: August 01, 1997
Web Site: http://oceancolor.gsfc.nasa.gov/SeaWiFS/SEASTAR/SPACECRAFT.html



The commercial SeaStar satellite carries the SeaWiFS instrument, which is designed to monitor the color of the world's oceans, and is a follow-on to the Coastal Zone Color Scanner (CZCS). Various ocean colors indicate the presence of different types and quantities of marine phytoplankton, which play a role in the exchange of critical elements and gases between the atmosphere and oceans. The satellite monitors subtle changes in the ocean's color to assess changes in marine phytoplankton levels, and provides data to better understand how these changes affect the global environmental and the oceans' role in the global carbon cycle and other biogeochemical cycles. Complete coverage of the Earth's oceans occurs every two days.

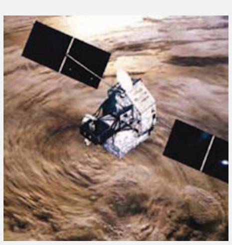
Solar Radiation and Climate Experiment (SORCE)
Launch Date: January 25, 2003
Web Site: http://lasp.colorado.edu/sorce

Solar radiation is the dominant, direct energy input into the terrestrial ecosystem, and it affects all physical, chemical, and biological processes. SORCE provides state-of-the-art measurements of incoming x-ray, ultraviolet, visible, near-infrared, and total solar radiation. The measurements provided by SORCE specifically address long-term climate change, natural variability and enhanced climate prediction, and atmospheric ozone and UV-B radiation. These measurements are critical to studies of the Sun, its effect on our Earth system, and its influence on humankind. Data obtained by the SORCE experiment is used to model the Sun's output and to explain and predict the effect of the Sun's radiation on the Earth's atmosphere and climate.

Terra
Launch Date: December 18, 1999
Web Site: http://terra.nasa.gov

Terra provides global data on the state of the atmosphere, land, and oceans, as well as their interactions with solar radiation and with one another. Terra's five instruments simultaneously study clouds, water vapor, aerosol particles, trace gases, terrestrial and oceanic surface properties, biological productivity of the land and oceans, the interaction among them and their effects on atmospheric radiation and climate. Comprehending these interactive processes is essential to understanding global climate change.

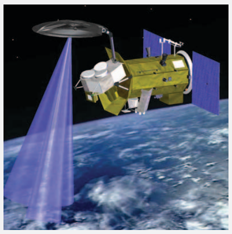
Tropical Rainfall Measuring Mission (TRMM)
Launch Date: November 27, 1997
Web Site: http://trmm.gsfc.nasa.gov



TRMM is the world's foremost satellite for the study of precipitation and associated storms and climate processes in the tropics and subtropics, contributing to a better understanding of where and how much the winds blow, where the clouds form and rain occurs, where floods and droughts. The tropical regions make up about two thirds of the total rainfall on Earth and are responsible for driving our weather and climate system. TRMM has evolved from an experimental mission focusing on tropical rainfall climatology into primary satellite in a system of research and operational satellites used for analyzing precipitation characteristics on time scales from 3-hr to inter-annually and beyond.

Appendix B — NASA Earth Science Foundational Missions Currently In Development

Aquarius
Launch Date: May 2010
Web Site: http://aquarius.gsfc.nasa.gov



Aquarius is a mission to measure changes in global sea surface salinity equivalent to about a "pinch" (i.e., 1/6 of a teaspoon) of salt in 1 gallon of water. By measuring sea surface salinity over the globe with such unprecedented precision, Aquarius will answer long-standing questions about how our oceans respond to climate change and the water cycle. Monthly sea surface salinity maps will give clues about changes in freshwater input and output to the ocean associated with precipitation, evaporation, ice melting, and river runoff. Aquarius data will also be used to track the formation and movement of huge water masses that regulate ocean circulation and Earth's climate. Within two months of starting observations, Aquarius will collect as many sea surface salinity measurements as the entire 125-year historical record from ships and buoys, and provide measurements over the 25 percent of the ocean where no previous observations have been made.

Glory
Launch Date: Late 2010
Web Site: http://glory.gsfc.nasa.gov

Glory is designed to help understand the Earth's energy balance and the effect on climate requires measuring black carbon soot and other aerosols, and the total solar irradiance. These measurements continue and improve upon NASA's research of the forcings influencing climate change in the atmosphere. Measurements produced by this mission and the scientific knowledge such observations will provide are essential to predicting future climate change, and to making sound, scientifically based economic and policy decisions related to environmental change.

Global Precipitation Measurement (GPM)
Launch Date: June 2013
Web Site: http://gpm.gsfc.nasa.gov

Building upon the success of the Tropical Rainfall Measuring Mission (TRMM), GPM will initiate further measurement of global precipitation, a key climate factor. GPM Constellation consists of a core spacecraft to measure precipitation structure and to provide a calibration standard for the constellation spacecraft, an international constellation of NASA and contributed spacecraft to provide frequent precipitation measurements on a global basis, calibration/validation sites distributed globally with a broad array of precipitation-measuring instrumentation, and a global precipitation data system to produce and distribute global rain maps and climate research products. These measurements will help improve the accuracy of weather and precipitation forecasts through more accurate measurement of rain rates and latent heating.

Landsat Data Continuity Mission (LDCM)
Launch Date: December 2012
Web Site: http://ldcm.nasa.gov

LDCM is a joint initiative of the U.S. Geological Survey (USGS) and the NASA to gather Earth resource data, and is a follow-on to Landsat 7, the most recent in a long series of Landsat satellites going back 30 years to 1974. One of the key objectives of LDCM is to make all Landsat-type data available at affordable cost. This will enable the many different sectors of the population—farmers, business leaders, scientists, educators, state and federal governments and many others to continue to utilize this data for high quality research and applications.

NPOESS Preparatory Project (NPP)
Launch Date: January 2011
Web Site: http://jointmission.gsfc.nasa.gov

The five sensors on NPP will collect data on atmospheric and sea surface temperatures, humidity, biological productivity, cloud and aerosol properties, the Earth's energy bud¬get, and atmospheric ozone. These data will be used for long-term climate and global change studies and serve as a continuation of measurements from NASA's Terra and Aqua satellites. In addition, NPP provides the agencies developing NPOESS with early access to the next generation of operational sensors, thereby greatly reducing the risks incurred during the transition. This will permit testing of the advanced ground operations facilities and validation of sensors and algorithms while the current operational and scientific systems are still in place. This new system will provide nearly an order of magnitude more data than the current operational system and will move a subset of critical climate quality Earth system data records into operational production.

Appendix C — NRC Decadal Survey Tier 1 Missions

Climate Absolute Radiance and Refractivity Observatory (CLARREO)
Launch Date: TBD
Web Site: http://clarreo.larc.nasa.gov

CLARREO is a joint NASA-NOAA mission recommended in the Decadal Study report of the National Research Council (NRC), "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond", to measure solar irradience. The NOAA component involves the continuity of measurements of incident solar irradiance and Earth energy budget by flying two sensors that were removed from NPOESS. The NASA portion involves the measurement of thermal infrared and reflected solar radiation at high absolute accuracy. These measurements will provide a long-term benchmarking data record for the detection, projection, and attribution of changes in the climate system. In addition, these measurements will provide a source of absolute calibration for a wide range of visible and infrared Earth observing sensors, greatly increasing their value for climate monitoring.

Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI)
Launch Date: TBD
Home Page: http://desdyni.jpl.nasa.gov

DESDynI was recommended in the Decadal Study report of the National Research Council (NRC), "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond", for measuring surface deformation, which is linked directly to earthquakes, volcanic eruptions, and landslides. Observations of surface deformation are used to forecast the likelihood of earthquakes occurring as a function of location, as well as predicting both the place and time when volcanic eruptions and landslides are likely. Advances in earthquake science leading to improved time-dependent probabilities would be significantly facilitated by global observations of surface deformation, and could result in significant increases in the health and safety of the public due to decreased exposure to tectonic hazards. Monitoring surface deformation is also important for improving the safety and efficiency of extraction of hydrocarbons, for managing our ground water resources, and, in the future, providing information for managing CO_2 sequestration.

Ice, Cloud, and land Elevation Satellite II (ICESat-II)
Launch Date: Late 2014/early 2015
Web Site: http://icesat.gsfc.nasa.gov/index.php

As envisioned by the Decadal Study, the ICESat-II mission will deploy an ICESat follow-on satellite to continue the assessment of polar ice changes by providing multi-year elevation data needed to determine ice sheet mass balance as well as cloud property information, especially for stratospheric clouds which are common over polar areas. ICESat-II is also expected to measure vegetation canopy heights, allowing estimates of biomass and carbon in above ground vegetation in conjunction with related missions, and allow measurements of solid earth properties.

Soil Moisture Active-Passive (SMAP)
Launch Date: Late 2013/early 2014
Web Site: http://smap.jpl.nasa.gov

The SMAP mission was recommended by the NRC Earth Science Decadal Survey Panel to provide direct measurement of surface soil moisture amd freeze-thaw state. Direct measurements of these properties are necessary to improve our understanding of regional water cycles, ecosystem productivity, and processes that link the water, energy, and carbon cycles. Soil moisture information at high resolution enables improvements in weather forecasts, flood and drought forecasts, and predictions of agricultural productivity and climate change.

Appendix D—Current Measurements and Planned Replacements for Data Continuity

Table 3. NASA Earth Science Missions Currently in Operation

Mission/ Launch Year	Instruments	Measurements	Potential Replacements
TRMM–1997		Global distribution of tropical rainfall*	GPM (2013, 2015)
	Precipitation Radar	Rain rate, rain drop size	PR: on GPM (2013)
	VIRS	Cloud coverage, height, and temperature	
	TMI	Microwave brightness temperatures	GMI: on GPM (2013, 2015)
	LIS	Lightning incidence	
	CERES (inoperative)	Earth radiation budget	CERES: on NPP (2011), NPOESS (2013)
Landsat 7–1999	NOTE: Operated by U.S. Geological Survey		
	ETM+	Land cover	LDCM (2012)
QuikSCAT–1999	SeaWinds	Ocean surface wind speed and direction	NOAA's XOVWM (TBD): possibly on JAXA GCOM-W2
Terra–1999	MODIS	Multiple (vegetation, clouds, ocean color, etc.)	VIIRS: on NPP (2011), NPOESS C1 (2013)
	MISR	Aerosol distributions	APS: on Glory (2010); ACE (Tier 2 mission in Decadal Survey)
	MOPITT (Canada)	Carbon monoxide and methane	
	ASTER (Japan)	Land surface imaging	OLI & TIRS: on LDCM (2012)
	CERES	Earth radiation budget	CERES: on NPP (2011), NPOESS C1 (2013)
ACRIMSAT–1999	ACRIM III	Total solar irradiance	SORCE since 2003; TIM: on Glory (2010); TSIS: on NPOESS C1 (2013)
EO-1–2000	ALI	Land cover	
	Hyperion	Hyperspectral land imaging	HyspIRI (Tier 2 mission in Decadal Survey)
	LAC	Atmospheric correction	
Jason–2001		Ocean surface topography*	OSTM since 2008; NOAA's Jason-3 (TBD); NASA's SWOT (Tier 2 mission in Decadal Survey)
	Poseidon-2 Altimeter (France)		
	Jason Microwave Radiometer		
	DORIS (France)		
	TurboRogue Space Receiver (a GPS)		
	Laser retroreflector		

Mission/ Launch Year	Instruments	Measurements	Potential Replacements
GRACE–2002		Earth's gravity field*	GRACE II (Tier 3 mission in Decadal Survey)
	High Accuracy Intersatellite Ranging System		
	ONERA SuperStar accelerometer		
	BlackJack GPS Receiver		
	Star Camera Assembly		
	Ultra Stable Oscillator		
Aqua–2002	MODIS	Multiple (vegetation, clouds, ocean color, etc.)	VIIRS: on NPP (2011), NPOESS C1 (2013)
	AIRS		
	AMSU-A	Upper atmosphere temperature profiles	ATMS, CrIS: on NPP (2011), NPOESS C1 (2013)
	HSB (Brazil) (inoperative)	Humidity profiles thru the atmosphere	ATMS, CrIS: on NPP (2011), NPOESS C1 (2013)
	AMSR-E (Japan)	Microwave brightness temperatures (winds, SST, ice, etc.)	JAXA's AMSR: on GCOM-W1 (2012); MIS: on NPOESS C2 (2016)
	CERES	Earth radiation budget	CERES: on NPP (2011), NPOESS (2013)
ICESat–2003	GLAS	Ice sheet topography	ICESat II (2014/2015)
SORCE–2003	TIM	Total solar irradiance	TIM: on Glory (2010); TSIS: on NPOESS C1 (2013)
	SOLSTICE, SIM, XPS	Solar spectral irradiance*	
Aura–2004	MLS	Upper atmosphere chemistry	GACM (Tier 3 mission in Decadal Survey)
	TES	Lower atmosphere chemistry	GEO-CAPE, GACM (Tier 2 & 3 missions in Decadal Survey)
	HIRDLS (UK) (not collecting data)	Upper atmosphere chemistry	
	OMI (Netherlands)	Total ozone and aerosols	Total ozone OMPS: on NPP (2011), NPOESS (2013)
CloudSat –2006			
	Cloud Profiling Radar	Cloud structure & radiative properties*	ACE (Tier 2 mission in Decadal Survey)
CALIPSO–2006		Vertical structure & properties of clouds & aerosols*	APS: on Glory (2010)
	Cloud-Aerosol Lidar		
	Wide Field Camera		
	Imaging Infrared Radiometer		

Mission/ Launch Year	Instruments	Measurements	Potential Replacements
OSTM–2008	NOTE: Operated by	Ocean surface topography*	NOAA's Jason-3 (TBD); NASA's SWOT
	Poseidon-3 Altimeter (France)		
	Advanced Microwave Radiometer		
	DORIS (France)		
	GPS		
	Laser Retroreflector		

* All the instruments in this suite are used to produce the key measurement.

Table 4. NASA Earth Science Foundational Missions

Mission/ Launch Year	Instruments	Measurements	Precursor Missions
Aquarius–2010	Note: Joint NASA-Space Agency of Argentina (CONAE) mission	Sea surface salinity	
	Aquarius on SAC-D spacecraft		
Glory–2010		Aerosols; solar irradiance	
	Aerosol Polarimetry Sensor		Terra (MISR), CALIPSO
	Total Irradiance Monitor		ACRIMSAT, SORCE (TIM)
LDCM–2012	Note: Joint NASA-USGS mission	Multi-spectral land data	
NPP–2011			
	VIIRS	Multi-spectral imager/radiometer	Terra (MODIS), Aqua (MODIS)
	CrIS	Atmospheric profiler	Aqua (AIRS, AMSU-A, HSB)
	ATMS	Atmospheric profiler	Aqua (AIRS, AMSU-A, HSB)
	OMPS	Ozone monitoring	Aqua (OMI)
GPM–2014		Precipitation	
	GPM Microwave Imager		TRMM (TMI)
	Dual-frequency Precipitation Radar		TRMM (Precipitation Radar)

Table 5. NASA Earth Science Decadal Survey Missions

Mission/Launch Year	Measurements	Precursor Missions
SMAP - Late 2013/Early 2014	Soil moisture and freeze/thaw	
ICESat-II – Late 2014/Early 2015	Ice sheet height	ICESat
DESDynl (Tier 1 mission)	Surface and sea ice deformation; vegetation structures	
CLARREO (Tier 1 mission)	Solar radiation	
HyspIRI (Tier 2 mission)	Land surface composition	EO-1 (Hyperion)
ASCENDS (Tier 2 mission)	CO_2	
SWOT (Tier 2 mission)	Ocean, lake, and river water levels	OSTM
GEO-CAPE (Tier 2 mission)	Atmospheric gas; ocean color	Aura (TES)
ACE (Tier 2 mission)	Aerosol and cloud profiles; ocean color	Terra (MISR), CloudSat, CALIPSO (Cloud-Aerosol Lidar)
LIST (Tier 3 mission)	Land surface topography	
PATH (Tier 3 mission)	Temperature and humidity	
GRACE-II (Tier 3 mission)	Gravity fields	GRACE
SCLP (Tier 3 mission)	Snow accumulation	
GACM (Tier 3 mission)	Ozone and related gases	Aura (MLS, TES)
3D-Winds (Tier 3 mission)	Tropospheric winds	