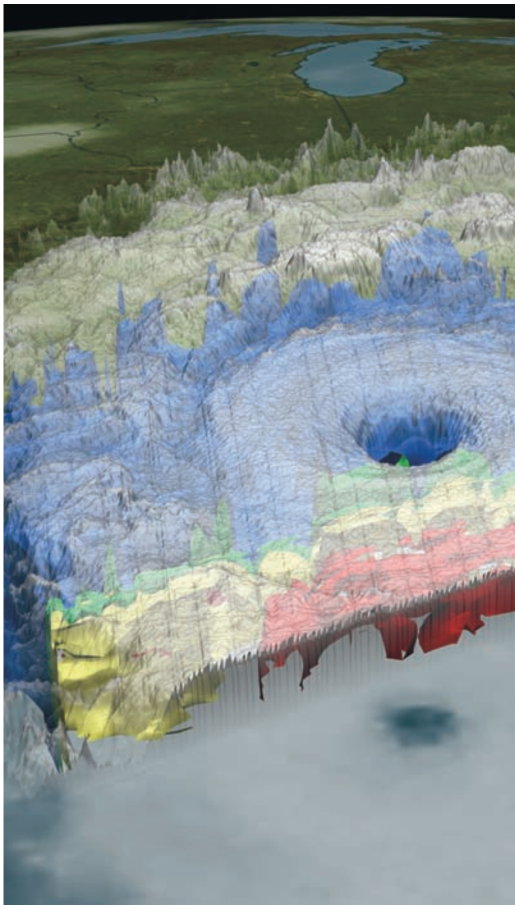
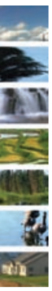




8 | Observing and Monitoring the Climate System

Observing and Monitoring the Climate System

Goal 12.1: Design, develop, deploy, and integrate observation components into a comprehensive system.
Goal 12.2: Accelerate the development and deployment of observing and monitoring elements needed for decision support.
Goal 12.3: Provide stewardship of the observing system.
Goal 12.4: Integrate modeling activities with the observing system.
Goal 12.5: Foster international cooperation to develop a complete global observing system.
Goal 12.6: Manage the observing system with an effective interagency structure.

Data Management and Information

Goal 13.1: Collect and manage data in multiple locations.
Goal 13.2: Enable users to discover and access data and information via the Internet.
Goal 13.3: Develop integrated information data products for scientists and decisionmakers.
Goal 13.4: Preserve data and information.

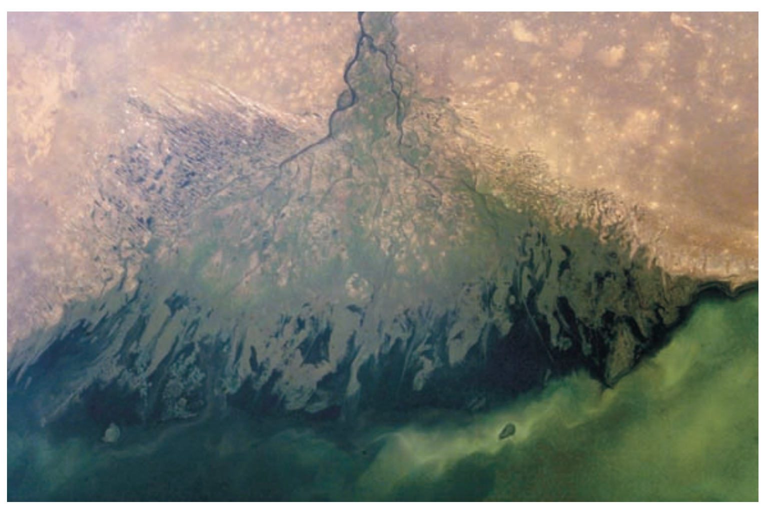
See Chapters 12 and 13 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of these goals.

The *CCSP Strategic Plan* identifies two overarching questions for "Observing and Monitoring the Climate System" (Chapter 12) and "Data Management and Information" (Chapter 13):

- How can we provide active stewardship for an observation system that will document the evolving state of the climate system, allow for improved understanding of its changes, and contribute to improved predictive capability for society?
- How can we provide seamless, platform-independent, timely, and open access to integrated data, products, information, and tools with sufficient accuracy and precision to address climate and associated global changes?

The United States is contributing to the development and operation of several global observing systems that collectively attempt to combine data streams from both research and operational observing platforms to provide a comprehensive measure of climate system variability and climate change processes. These systems provide a baseline Earth-observing system and include NASA, NOAA, and USGS Earth-observing satellites and extensive *in situ* observational capabilities. CCSP also supports several ground-based measurement activities that provide the data used in studies of the various climate processes necessary for better understanding of climate change. U.S. observational and monitoring activities contribute significantly to several international observing systems including the Global Climate Observing System principally sponsored by the World Meteorological Organization (WMO); the Global Ocean Observing System sponsored by the United Nations Educational, Scientific, and Cultural Organization's Intergovernmental Oceanographic Commission (IOC); and the Global Terrestrial Observing System sponsored by the United Nations Food and Agriculture Organization. The latter two have climate-related elements being developed jointly with the Global Climate Observing System.

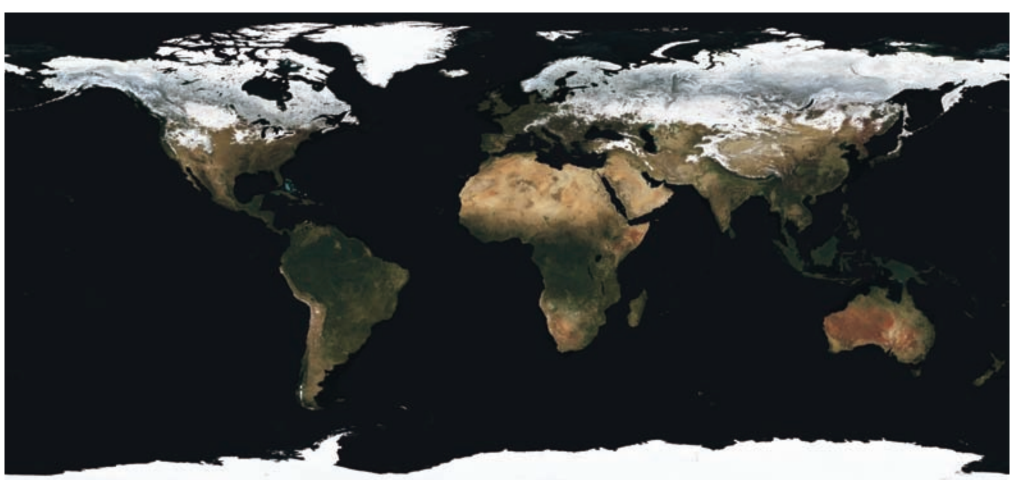
The United States is also playing an important role in the Global Earth Observation System of Systems (GEOSS), which is an international framework for coordinating and sustaining the aforementioned (and other) systems. Information from GEOSS is expected to revolutionize understanding of the Earth and how Earth observations may benefit society. A 10-year implementation plan for GEOSS was adopted in February 2005 by nearly 60 countries, including the United States (see <earthobservations.org> for a copy of this plan, as well as other information on GEOSS). The U.S. Group on Earth Observations (USGEO) has drafted a strategic plan for integrated Earth observations, which contributes directly to GEOSS. CCSP coordinates USGEO's climate and global change-related activities. USGEO is focusing on the following areas, many of which are directly or indirectly related to CCSP: understanding, assessing, predicting, mitigating, and adapting to climate variability and change; weather forecasting; reducing loss of life and property from disasters; protecting and monitoring ocean resources; supporting sustainable agriculture and combating land degradation; understanding the effect of environmental factors on human health and well-being; developing the capacity to make ecological forecasts; protecting and monitoring water resources; and monitoring and managing energy resources.



One of the priorities for observations and monitoring in FY 2007 is to further define the U.S. role in GEOSS, including the development of an information management system to help integrate the system's distributed resources. Another priority is to enhance observational capabilities in polar regions, both through remote-sensing and *in situ* approaches. These capabilities and approaches will converge on the International Polar Year (IPY) beginning in 2007, discussed briefly later in this chapter. Observations of aerosols and approaches outlined in the Atmospheric Composition chapter of this report are also a priority. Improving understanding of the carbon cycle, which CCSP has identified as a near-term priority, will be facilitated by enhanced observations in FY 2007 and beyond. A longer list of some of the planned observational and monitoring activities is provided later in this chapter. Data management and distribution activities, including those mentioned in the box on "Systems for Data Management and Distribution," will play a key role in making accessible the information necessary to fulfill CCSP's mission to provide the "Nation and the global community with the science-based knowledge to manage the risks and opportunities of change in the climate and related environmental systems."

Many measurement and monitoring technologies and derived data systems benefit from the ongoing research and development under the aegis of CCSP, and from other Earth observation activities that are currently underway. All such measurement and monitoring systems constitute an important component of and complement to the measurement and monitoring research and development portfolio of CCTP. For additional information on CCTP measurement and monitoring research and development activities, see <www.climatetechnology.gov>.

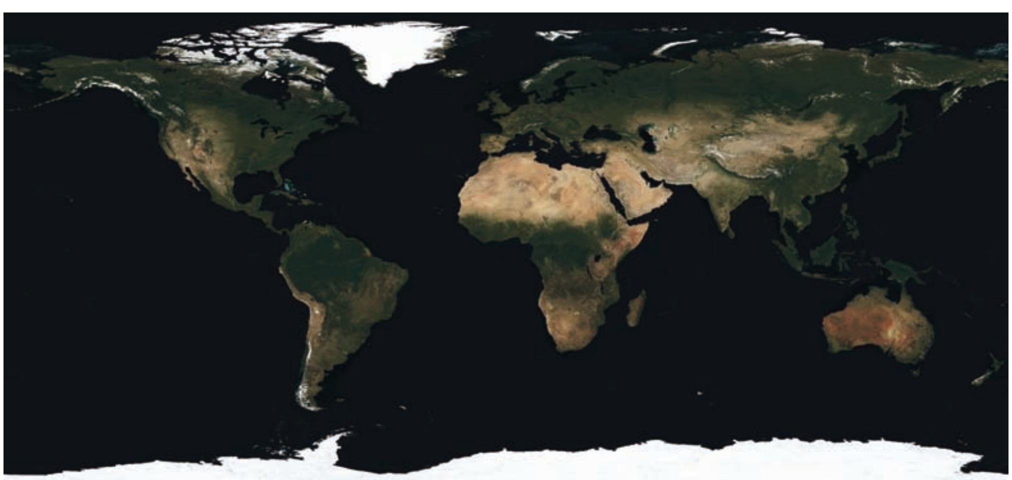
The Global Climate Observing System (GCOS) integrates global networks placed strategically across the atmospheric, oceanic, and terrestrial domains, permitting

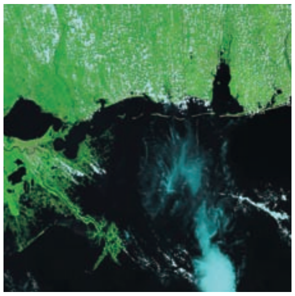


better understanding of climate variability and change. In recent years, GCOS has encouraged, coordinated, and facilitated a number of positive actions on international, regional, and bilateral levels that have led to success in improving climate observations worldwide. A number of workshops have been held in developing nations, highlighting the importance of GCOS observations. These workshops have resulted in a series of regional action plans that will help guide observational improvements in these regions. Spearheaded by the United States, a GCOS Cooperation Mechanism has been established to leverage the resources of developed nations to ensure that dormant GCOS network stations begin to be retrofitted. This will facilitate the collection of valuable surface and upper-air data used in climate studies (see, e.g., CCSP Synthesis and Assessment Product 1.1, which is briefly discussed in the Climate Variability and Change chapter).

The United States is making key ocean observations that are important to both science and society. They include sea-level observations, measured using tide gauge stations and satellite observations; ocean carbon sources and sinks; ocean storage and global transport of heat and freshwater; and exchange of heat and freshwater between the ocean and atmosphere. To collect data on these variables, it is necessary to enhance the *in situ* and satellite components of the global ocean observing system, including an array of sensors situated across the global oceans. The number of instruments being deployed in the oceanic observing networks is increasing steadily.

The United States has a three-tiered approach to *in situ* land-surface climate observations. In the first tier, a few sites, such as the Atmospheric Radiation Measurement (ARM) Program sites, are heavily instrumented, providing a vast array of frequent high-quality observations of virtually all key variables measurable from the surface. ARM operates sites in three primary locations (southern Great Plains, tropical western Pacific, and





North Slope of Alaska) identified as representing the range of climate conditions important for studying the effects of clouds on global climate change. In addition, the ARM Mobile Facility can perform atmospheric measurements similar to those at the fixed ARM sites for periods up to a year anywhere in the world. Data are collected continuously and are made available in near-real-time. Using these data, scientists are studying the effects and interactions of sunlight, radiant energy, and clouds to understand their impact on temperature, weather, and climate.

The second tier, known as the Climate Reference Network (CRN), will include more than 100 sites that make long-term, homogeneous observations of temperature and precipitation (and a few other variables) that can be coupled to long-term historical observations for the detection and attribution of present and future climate change. The USCRN program will provide the United States with a climate-monitoring network that meets national commitments to monitor and document climate change. The network will provide adequate spatial coverage to monitor annual and decadal-to-centennial temperature and precipitation trends at the national scale for the United States. The goal is to establish a network that 50 years from now will answer the question: How has the climate of the United States changed over the past 50 years? To date, 73 operational sites in the contiguous United States (60% of the network) have been deployed. Implementation of plans for an eventual network of 42 CRN sites in Alaska will begin in 2007. In addition, the CRN configuration will be used on a more global level to aid in establishing reference GCOS Surface Network (GSN) sites. Three such prototype GSN/CRN sites have been established in three locations in the Pacific (Hawaii and American Samoa). Observations that will be available from the USCRN are relevant to CCSP but not included in the budget cross-cut.

The third tier, which provides greater spatial coverage than the CRN, is composed of more than 1,000 stations in the existing Historical Climatology Network, selected based on homogeneity and quality standards. This tiered approach provides the spatial coverage necessary to detect regional climate variability and change, as well as the quality controls necessary to ensure that the observations are as bias-free as possible. U.S. contributions to GCOS also include ecosystem, hydrosphere, cryosphere, and atmospheric composition measurements.

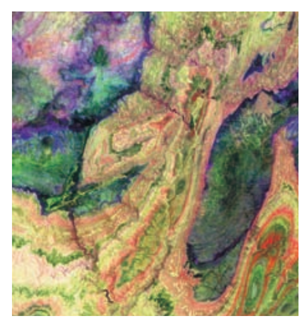
The top three priorities of CCSP relate to aerosols, the carbon budget, and polar climate/feedback. The Observations Working Group's contributions to those priorities include:

- Creation of a unified picture of global aerosol, cloud, CO_2, and ozone distributions from the A-train satellite constellation and related Earth-observing systems

- Identification of black carbon aerosol and other aerosol impacts on the water cycle, as measured by the Indian Ocean Experiment (INDOEX), the Coordinated Enhanced Observing Period (CEOP), and other *in situ* observations
- Determination of sea-ice concentrations from the Advanced Microwave Scanning Radiometer—EOS (AMSR-E), the Moderate-Resolution Imaging Spectroradiometer (MODIS), and Advanced Synthetic Aperture Radar (ASAR)
- Improvement of the accuracy of measurement systems—for example, reduced uncertainties in water vapor concentrations from 25% to less than 3%.

Additionally, important contributions to GCOS, which constitutes the formal climate component of GEOSS, have progressed, specifically:
- 56% completion of the initial Ocean Observing System for Climate
- 100% completion of the global drifting buoy array
- Extension of the tropical moored buoy network into the Indian Ocean
- Establishment of three GCOS regional Technical Support Centers for the Pacific Islands, East and South Africa, and the Caribbean/Central America
- 70% reduction in the number of "silent" GCOS Upper Air Network (GUAN) sites (i.e., those not providing data) in developing nations (from 20 to 6)
- Global rainfall and hurricane structure observations from more than 8 years of the Tropical Rainfall Measuring Mission (TRMM), which has led to improved tropical cyclone forecasts.

HIGHLIGHTS OF RECENT ACTIVITIES AND ACCOMPLISHMENTS



The following are selected highlights of observation and monitoring activities supported by CCSP-participating agencies. The principal focus of this chapter is on describing progress in implementing the observations that contribute to the CCSP mission. As a result, the chapter touches on some observing systems that are crucial to CCSP but are not included within the CCSP budget because they primarily serve other purposes.

Observations and Monitoring

Initial Ocean Observing System for Climate 56% Completed. The NOAA Office of Climate Observation cooperates with 66 nations in implementing the internationally vetted design of an initial ocean observing system for climate, articulated in the WMO/IOC/United Nations Environment Programme plan for GCOS. Deployment of the observing system, planned for completion in 2012, is proceeding on schedule, with the United States currently supporting over 50% of the ocean-based observing platforms.

Global Drifting Buoy Array 100% Completed. In an historic milestone for international cooperation, the global drifting buoy array achieved its design goal of 1,250 data buoys in sustained service, thus becoming the first component of the Global Ocean Observing System and of GEOSS to be fully implemented. The United States currently maintains 1,000 of the buoys in the array. These buoys provide the operational instrumental data sets for describing the evolution of ocean surface circulation and sea surface temperature, which are used for testing climate models and enhancing long-range weather and seasonal-to-interannual climate predictions.

Tropical Moored Buoy Network Extended into the Indian Ocean. Working in close collaboration with Japan and India, the first six of a series of moored buoys have been deployed in the Indian Ocean for measurement of a comprehensive suite of ocean-atmosphere climate variables. This westward extension of the equatorial Pacific Tropical Atmosphere Ocean/Triangle Trans-Ocean array, whose long-term data have revolutionized understanding of the evolution of El Niño, is necessary to understand changes in Indian Ocean sea surface temperatures, which have recently been shown to be a cause of regional climate variability and change (including prolonged drought in the mid-latitudes, including the United States).

Polar Region Observations.[1] Polar systems may be especially sensitive to climate change and might provide early indications of climate change. They also interact with climate variability and change through several important feedback processes. Monitoring polar climate and understanding its feedbacks are key priorities described in the *CCSP Strategic Plan*. CCSP supports the creation of systematic data sets for parameters such as sea-ice thickness, extent, and concentration; land-ice and snow-cover mass balance; and surface temperature. The *Arctic Climate Impact Assessment* highlighted the impacts of changes in these and other variables. NSF and NOAA are jointly implementing an interagency activity entitled the Study of Environmental Arctic Change (SEARCH) to better understand climate change as identified in the *Arctic Climate Impact Assessment* (see <www.arcus.org/search>).

Clues to Variability in Arctic Minimum Sea-Ice Extent.[7] Perennial sea ice is a primary indicator of Arctic climate change. From 1979 to 2003, it decreased in extent by about 17%. Analysis of new satellite-derived fields of winds, radiative forcing, and advected heat reveals distinct regional differences in the relative roles of these parameters in explaining variability in the northernmost ice-edge position. In all six peripheral seas studied, downwelling long-wave radiation flux anomalies explain the most variability—approximately 40%—while northward wind anomalies are important in areas north of Siberia, particularly earlier in the melt season. Anomalies in insolation are negatively correlated with perennial ice retreat in all regions, suggesting that the effect of solar flux anomalies is overwhelmed by the long-wave influence on ice edge position.

ICESat. Significant contributions are being made to CCSP's polar observations by NASA's Ice, Cloud, and Land Elevation Satellite (ICESat), launched in 2003 (see <icesat.gsfc.nasa.gov>). ICESat measures surface elevations of ice and land, vertical distributions of clouds and aerosols, vegetation canopy heights, and other features with unprecedented accuracy and sensitivity. The primary purpose of ICESat has been to acquire time series of ice-sheet elevation changes for determination of the present-day mass balance of the ice sheets, study of associations between observed ice changes and polar climate, and improvement of estimates of the present and future contributions to global sea-level rise. ICESat has achieved remarkable successes with a number of first-of-their-kind observations, including:

- The most accurate elevation maps to date of the Greenland and Antarctic ice sheets
- Detection of change in the Greenland and Antarctic ice sheets
- Demonstrated ability to characterize detailed topographic features of ice sheets, ice shelves, and ice streams
- Capability of detecting ice-sheet elevation changes as small as centimeters per year
- Pioneering sea-ice thickness mapping (distributions and means)

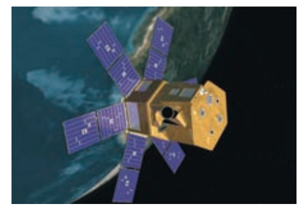
- Global mapping of cloud heights and aerosols with unprecedented sensitivity and detail
- Sensing of vegetation canopy heights and density
- Precision mapping of land elevations.

MODIS. The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument has been operating successfully on NASA's Earth Observing System (EOS) Terra mission for over 6 years and on the Aqua mission for over 4 years. The MODIS instruments have provided daily global observations of land, ocean, and atmospheric features with unprecedented detail, due to the 250- to 1,000-m spatial resolution coupled with multi-spectral capability in 36 carefully selected bands extending from the visible to the thermal infrared portions of the electromagnetic spectrum.

In the case of atmospheric features, MODIS has produced advanced, detailed observations of the global and regional extent of aerosols from natural and anthropogenic activity. MODIS not only observes more accurately the extent of cloudiness, including that associated with thin, wispy cirrus, that profoundly affects Earth's radiation balance, but also cloud properties such as cloud phase (water or ice), optical depth (i.e., cloud thickness), and effective droplet radius. MODIS is also providing more detailed observations of land features such as surface reflectance (albedo), surface temperature, snow and ice cover, and the variability of vegetation type and vigor associated with seasonal and climatic (e.g., above and below average moisture) variability. The capability of MODIS to classify vegetation types and the photosynthetic activity of vegetation over the land as well as in the surface waters of the world's oceans (i.e., phytoplankton) is leading to more accurate evaluation of spatial and seasonal changes in the global net productivity of Earth's biosphere. MODIS' capability for observing global processes and trends is leading to better understanding of natural and anthropogenic effects on the Earth-atmosphere system, and to better performance of general circulation models (GCMs). An example of the latter is the use of atmospheric winds derived from MODIS observations over the polar regions of the globe. These observations have been shown to improve the global predictive skill of several GCMs, both in the polar regions that are undergoing rapid change, and in the mid-latitudes.

More than 100 "Direct-Broadcast" stations are now operating across the globe, enabling MODIS data to be obtained in near-real-time from the Aqua and Terra missions. About 800 user agencies or entities are now routinely using MODIS observations for regional applications or studies, including, for example, assessing the clarity of lakes (e.g., in Wisconsin and Minnesota), using observations of fire occurrence to strategically allocate fire-fighting resources (e.g., the U.S. Forest Service), and monitoring the extent of pollution (e.g., in China).

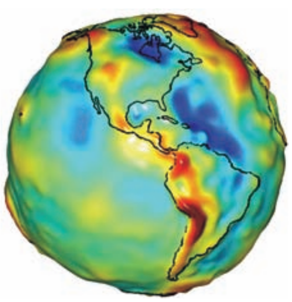
QuikSCAT.[2,6] The SeaWinds instrument aboard the Quick Scatterometer (QuikSCAT) satellite has measured the speed and direction of wind over the surface of the oceans since 1999. Although launched as an experimental instrument, it has been assimilated pre-operationally into atmospheric weather prediction models (NOAA's National Centers for Environmental Prediction, the European Centre for Medium-Range Weather Forecasts, and others) for the past 2 years. It is providing new insights on air-sea exchanges. Furthermore, the underlying radar backscatter data have been applied to climate change research concerning terrestrial high latitudes through studies of ice-layer formation.



Solar Variability: SORCE. The Sun is the Earth's primary energy source and external driver of climate variability. The Solar Radiation and Climate Experiment (SORCE) satellite, launched in 2003, is equipped with four instruments that measure variations in solar radiation much more accurately than previous instruments. SORCE is now making the first contiguous observations of solar variability across the full solar spectrum, from the far ultraviolet to near-infrared wavelengths. In June 2004, SORCE measured small changes in solar luminosity caused by the transit of Venus, demonstrating unprecedented precision. On 4 November 2004, SORCE documented the largest solar X-ray flare ever recorded and measured associated changes in total solar irradiance. SORCE's operational life is expected to extend across the upcoming 2006-2007 solar minimum, a crucial period for estimating any long-term trend, such as that indicated by indirect measurements of past solar forcing. SORCE is expected to overlap with the Glory mission that will carry forward the total solar irradiance record after 2008, as discussed below. The continued measurements previously planned by the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) through the Total Solar Irradiance Sensor (including a Total Solar Irradiance Monitor and Spectral Irradiance Monitor) were removed from the NPOESS program during the Nunn-McCurdy recertification process completed in June 2006. Agencies are currently assessing the impacts of this decision for solar irradiance monitoring.

Constellation Observing System for Meteorology, Ionosphere, and Climate. The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) relies on radio occultation of signals from the Global Positioning System satellites. COSMIC satellites will take 2,500 vertical profile measurements every 24 hours in a nearly uniform distribution around the globe, filling in current data gaps over vast stretches of the oceans. The data's high vertical resolution will complement the high horizontal resolution of other conventional weather satellite measurements. This will be the first time that the technique of radio occultation will be used on a large scale in real-time to provide continuous monitoring of worldwide atmospheric conditions. COSMIC builds on a series of previous research-oriented satellites, which were used to develop the measurement technique and establish the usefulness of the data in operational forecast systems. The remarkable stability, consistency, and accuracy of the measurements should be a boon to scientists quantifying long-term climate change trends. COSMIC was successfully launched on 14 April 2006, and its constellation of six small satellites will be transmitting atmospheric data to Earth for the next 5 or more years.

ARM Mobile Facility. The primary goal of the ARM Program is to improve the treatment of cloud and radiation physics in global climate models in order to improve the climate simulation capabilities of these models. These efforts have been enhanced by the addition of the ARM mobile facility (AMF) to study cloud and radiation processes in multiple climatic regimes. AMF can be deployed to sites around the world for durations of 6 to 18 months. Data streams produced by AMF will be available to the atmospheric community for use in testing and improving parameterizations in global climate models. The first deployment of AMF, in Point Reyes California—a collaboration between DOE and the DOD Office of Naval Research—made observations of marine stratus clouds and cloud-aerosol interactions (see <www.arm.gov/sites/amf.stm>).



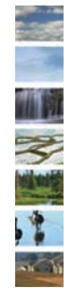
Observing Earth's Mass Distribution Changes from Space.[3,4,8] The Gravity Recovery and Climate Experiment (GRACE) is a two-spacecraft mission, developed under a partnership between NASA and the German Aerospace Center. After two successful years of mission operation, significant multidisciplinary results using GRACE observations are being reported. The unprecedented accuracy of the measurements provides the opportunity to observe time variability in the Earth's gravity field due to changes in mass distribution. Large variations in mass distribution occur predominantly over the continents, but smaller and slower signals caused by changes in ocean circulation and land ice sheets and glaciers are also detectable. One analysis using GRACE data determined that up to 10 cm (4 in) of groundwater accumulation is associated with heavy tropical rains, particularly in the Amazon Basin and Southeast Asia.

Major climate events also influence Earth's shape due to changes in the mass of water stored in oceans, continents, and the atmosphere. Over the past 3 decades, geodetic observations using satellite-laser ranging techniques have detected large-scale changes in the Earth's oblateness. Researchers found that in the past 28 years, two large variations in Earth's oblateness were connected with strong ENSO events. Longer term changes in Earth's oblateness are explained by the redistribution of mass in the Earth's mantle due to the slow release of stress from the weight of ice on landmasses during the last glaciation. However, the data sets show that the long-term post-glacial rebound was interrupted by an anomaly in oblateness during the period 1998 to 2002, although the geophysical cause of this anomaly remains unidentified.

Data Management and Information

The paragraph that follows and the accompanying text box highlight selected data management and information activities supported by CCSP-participating agencies.

REASoN Program. Forty Cooperative Agreement projects that are part of NASA's Earth Science Research, Education, and Applications Solutions Network (REASoN)



SYSTEMS FOR DATA MANAGEMENT AND DISTRIBUTION

Cooperative efforts by NASA, NOAA, and other CCSP agencies are moving toward providing an integrated and more easily accessed Earth information system that will effectively preserve, extend, and distribute information about the evolving state of the Earth. A few examples of specific agency efforts are given below. Although each activity has a single lead agency, participation involves many CCSP agencies, as well as State, local, and nongovernmental partners.

These activities address Goals 12.3, 12.6, 13.1, 13.2, and 13.4 of the CCSP Strategic Plan.

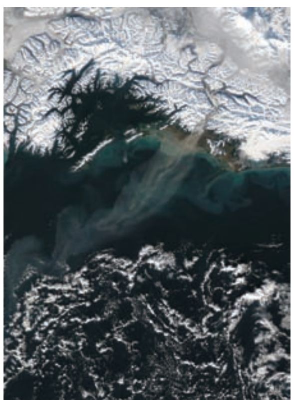
Earth Observing System Data and Information. NASA's Earth Observing System Data and Information System (EOSDIS) provides convenient mechanisms for locating and accessing products of interest either electronically or via orders for data on media. EOSDIS facilitates collaborative science by providing sets of tools and capabilities such that investigators may provide access to special products (or research products) from their own computing facilities. EOSDIS has an operational EOS Data Gateway (EDG) that provides access to the data holdings at all the Distributed Active Archive Centers (DAACs) and participating data centers from other U.S. and international agencies. Currently, there are14 EDGs around the world that permit users to access Earth science data archives, browse data holdings, select data products, and place data orders.

Distributed Active Archive Centers. Eight NASA DAACs, representing a wide range of Earth science disciplines, comprise the data archival and distribution functions of EOSDIS. DAACs are responsible for processing certain data products from instrument data, archiving and distributing NASA's Earth science data, and providing a full range of user support. There are more than 2,100 distinct data products archived at and distributed from the DAACs. These institutions are custodians of Earth science mission data until the data are moved to long-term archives. They ensure that data will be easily accessible to users. NASA and NOAA have initiated a pilot project to develop a prototype system for testing approaches for moving MODIS data into long-term NOAA archives. This pilot project is part of the evolution of the Comprehensive Large Array-data Stewardship System (CLASS) developed by NOAA. Acting in concert with their users, DAACs provide reliable, robust services to those whose needs may cross traditional discipline boundaries, while continuing to support the particular needs of their respective disciplines. DAACs are serving a broad and growing user community at an increasing rate.

Global Change Master Directory. The Global Change Master Directory (GCMD) is an extensive directory of descriptive and spatial information about data sets relevant to global change research. GCMD provides a comprehensive resource where a researcher, student, or interested individual can access sources of Earth science data and related tools and services. At present the GCMD database contains over 17,200 metadata descriptions of data sets from more than 1,200 government agencies, research institutions, archives, and universities worldwide; updates are made at the rate of 900 descriptions per month. GCMD contains descriptions of data sets covering all disciplines that produce and use data to help understand our changing planet. Although much research is focused on climate change, GCMD includes metadata from disciplines including atmospheric science, oceanography, ecology, geology, hydrology, and human dimensions of climate change. This interdisciplinary approach is aimed at researchers exploring the interconnections and interrelations of multidisciplinary global change variables (e.g., how climate change may affect human health). GCMD has made it easier for such data users to locate the information they desire. A portal has been created in support of GEOSS. The professional relationship between the system developers and the scientists has yielded an environment where the developers respond to the needs of potential users (see <gcmd.nasa.gov>).

Carbon Dioxide Information Analysis Center. DOE's Carbon Dioxide Information Analysis Center (CDIAC) provides comprehensive, long-term data management support, analysis, and information services to DOE's climate change research programs, the global climate research community, and the general public. The CDIAC data collection is designed to answer questions pertinent to both the present-day carbon budget and temporal changes in carbon sources and sinks. The data sets are designed to provide quantitative estimates of anthropogenic CO_2 emission rates, atmospheric concentration levels, land-atmosphere fluxes, ocean-atmosphere fluxes, and oceanic concentrations and inventories. CDIAC provides unrestricted, free distribution of its data products.

have completed their first year. The REASoN projects are part of NASA's strategy to work with its partners to improve its existing data systems, guide the development and management of future data systems, and focus performance outcomes to further Earth science research objectives. In order to achieve these goals, the REASoN projects are organized to engage the science community and peer review process in the development of higher level science products; to use these products to advance Earth system research; to develop and demonstrate new technologies for data management and distribution; and to contribute to interagency efforts to improve the maintenance and accessibility of data and information systems. A list of ongoing activities under this program is available at <research.hq.nasa.gov/code_y/nra/current/CAN-02-OES-01/winners.html>.



Highlights of Plans for FY 2007

CCSP will support the development and implementation of integrated systems for observations and monitoring of climate and global change, and associated data management and information systems. Selected key planned activities for FY 2007 and beyond follow.

Polar Region Observations: International Polar Year (IPY). Polar climate observations will continue to be a CCSP focus as preparations are made for IPY, which will begin in March 2007. IPY coincides with the 50th anniversary of the International Geophysical Year, which in 1957 initiated the systematic observation of key climate variables, such as atmospheric CO_2, and set the stage for the era of satellite observations. Data from space-based observatories as well as more traditional surface-observatories will provide high-quality records needed to detect potential future climate changes in the cryosphere.

The United States plans to increase its efforts on observations of the polar atmosphere, ice, and ocean, as well as leverage its investments in polar research with international partners. Working with Canada, NOAA and NSF will deploy an atmospheric observatory in northeastern Canada to mirror current activities in Barrow, Alaska. Together, these observatories will provide an improved high-resolution characterization of clouds and aerosols, and of incoming and outgoing radiation. Two NASA satellites launched on 28 April 2006, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and Cloudsat, use lidar and radar to provide three-dimensional distributions of aerosols and layered clouds. Surface field teams from many nations will be supported by a wealth of satellites contributed for polar research by multiple space agencies. Calibration and validation field programs utilizing airborne and balloon-borne sensors

associated with these satellite missions and other programs will greatly aid in the characterization of accelerating changes in the Arctic and Antarctic.

Research vessels from various Arctic countries will join the United States in coordinated measurements at ocean gateways through which waters are exchanged between the polar and temperate latitudes. Buoys will be deployed to extend the observations through and beyond the IPY. Additional effort will be made to detect changes in sea ice through direct measurement of sea-ice properties, and also through satellite sensors (see, e.g., ICESat description above) whose calibration can be enhanced by the availability of an increased set of buoy data. Changes in the temperature and salinity structure of the ocean beneath sea ice could be a critical indicator of changes in the climate system, and new efforts will be made to gather such data. The Bering, Chukchi, and Beaufort Seas off Alaska are home to many valuable living resources, including fish, marine mammals, and birds, that are affected by ocean currents and the seasonal progression of sea ice. These areas are warming rapidly and the annual period of ice cover is diminishing. The biotic response to these physical changes will be studied through enhanced observations by automated systems and ship-based activities.

In addition to the deployment of an additional 16 CRN stations in the contiguous United States, operational deployment of the eventual network of 42 Alaskan CRN stations is scheduled to begin with an initial four stations; this is in addition to a set of four prototypes that were deployed in FY 2005.

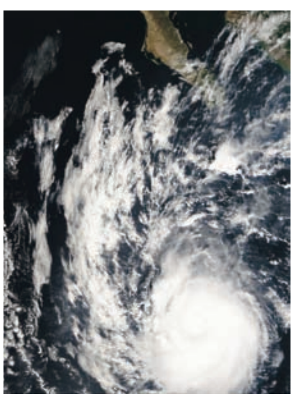
Lasting 24 months, IPY will include two summer field seasons in both hemispheres, permitting more extensive observations and helping to establish a durable network of polar observatories supported by numerous polar countries. IPY links to the Electronic Geophysical Year are intended to make IPY data sets more accessible for scientific and policy use (see <www.us-ipy.org> and <www.egy.org>).

These activities will address Goals 12.1 and 12.5 of the CCSP Strategic Plan.

Global Climate Observing System. FY 2007 will see continued growth in the deployment of the global ocean observing component of the U.S. Integrated Ocean Observing System (IOOS), which is the major U.S. contribution to the Global Ocean Observing System (GOOS), and the climate and ocean components of GEOSS. Working in close cooperation with international partners, incremental advances will be made in all ocean observing networks, which will boost the system to 61%

completion of the initial ocean observing system design, as articulated in the internationally vetted GCOS implementation plan (GCOS-92). FY 2007 priorities for advancement of the atmospheric and ocean observing components of GCOS include the following:

- Reduce the uncertainty in estimates of changes in the carbon inventory of the global ocean. The immediate plan will be to add autonomous CO_2-sampling instrumentation to the moored arrays and ships of opportunity to analyze seasonal variability and long-term trends in carbon exchange between the ocean and atmosphere.
- Reduce uncertainties in sea-level change and sea surface temperature. The immediate plan is to complete the global subset of tide gauge stations, identified as the ocean reference network, for altimeter calibration and detection of long-term trends.
- Document the ocean's heat storage and transport to identify where anomalies enter the ocean, how they move and are transformed, and where they re-emerge to interact with the atmosphere. The immediate plan is to advance the implementation of a global network of ocean reference stations to provide validation points for climate forecast and projection models, monitor key locations in the ocean for signs of possible abrupt climate change, and enhance data collection from ships of opportunity, thus completing a subset of high accuracy lines to be frequently repeated and sampled at high resolution for systematic upper ocean and atmospheric measurements. In addition, the 2005 hurricane season demonstrated the need for better understanding and forecasting of hurricane development; accordingly, a subset of special hurricane drifters (drifting data buoys) will be air-deployed directly in the path of approaching hurricanes to measure the ocean's heat energy potential.



- Document changes in the ocean's contributions to the global water cycle. The immediate plan is to instrument the global arrays of moored and surface drifting buoys and ships of opportunity for measuring sea surface salinity, a direct indicator of the ocean's evaporation and precipitation.
- Retrofit GUAN sites in developing nations through the provision of expendable equipment (e.g., radiosondes and balloons), and install new reference GSN sites in developing nations and unique climate regimes.
- Monitoring the health of the GCOS networks is vital to ensure that possible problems with data quality are caught and fixed early, so that vital data sets retain their integrity and utility as input to global assessments of climate as performed by the Intergovernmental Panel on Climate Change.
- A number of other associated GCOS activities involve the data quality and calibration of global data sets of precipitation chemistry, solar radiation, and regional precipitation networks, as well as support for GCOS-related research activities such as the African Monsoon Multidisciplinary Analysis project and basic support for the international GCOS secretariat.

These activities will address Goals 12.3 and 12.5 of the CCSP Strategic Plan.

ARM Mobile Facility. In FY 2007, the AMF will be deployed to a low-mountain region in Germany with the objective of improving quantitative precipitation forecasts. The AMF instruments will strongly support the goal of determining three-dimensional distributions of atmospheric variables.

These activities will address Goals 12.3 and 12.5 of the CCSP Strategic Plan.

Earth System Science Pathfinder Program. NASA's Earth System Science Pathfinder (ESSP) program is the primary source of exploratory missions to complement the EOS satellites Terra, Aqua, and Aura. The ESSP program consists of smaller missions developed and implemented on a faster schedule, proposed by the scientific community to address specific research questions. The first ESSP mission, GRACE, was launched in March 2002. A second launch on 28 April 2006 deployed two more ESSP satellites, CloudSat and CALIPSO, as mentioned in the previous subsection. After initial testing and quality control, data from these key missions were made available in mid-2006.

CloudSat, a joint mission involving NASA, the U.S. Air Force, and the Canadian Space Agency, is designed to measure cloud properties that are critical for understanding cloud effects on both weather and climate. These cloud properties are not obtainable from current satellite measurement systems. The mission's primary science goal is to furnish data needed to evaluate and improve the way clouds are parameterized in global models, thereby contributing to better predictions of clouds and to a better understanding of poorly understood cloud-climate feedbacks. CloudSat's key observations are the vertical profiles of cloud liquid- and ice-water content and related

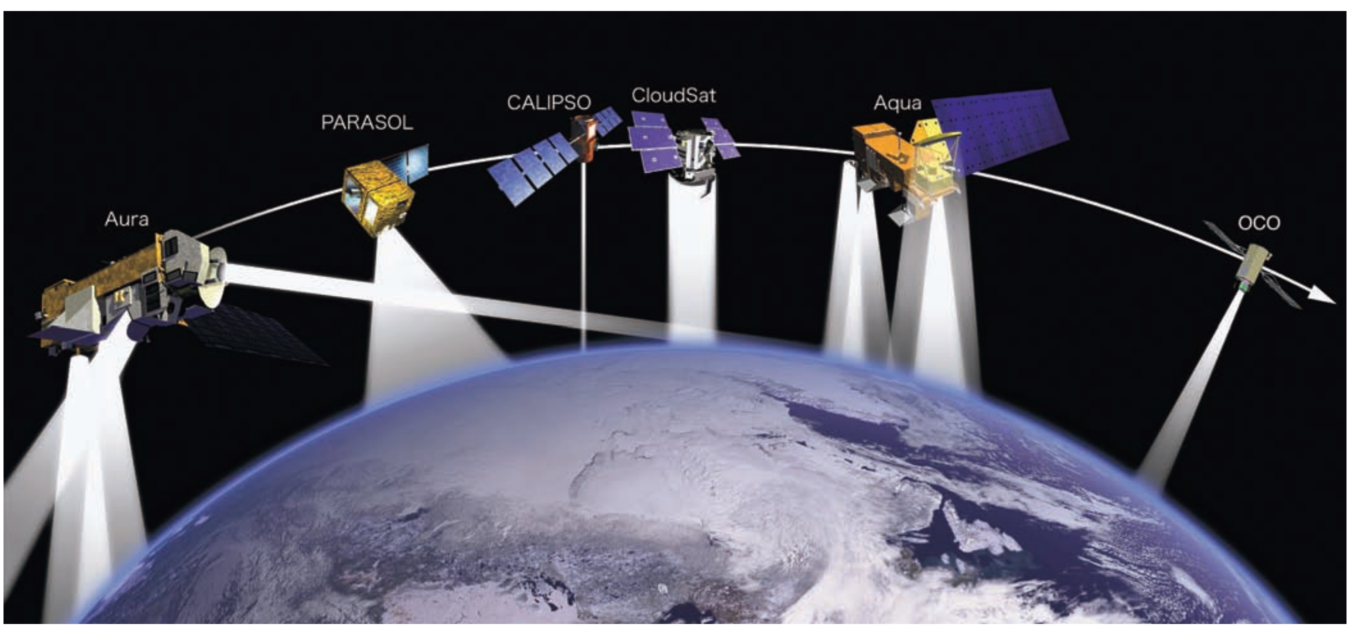
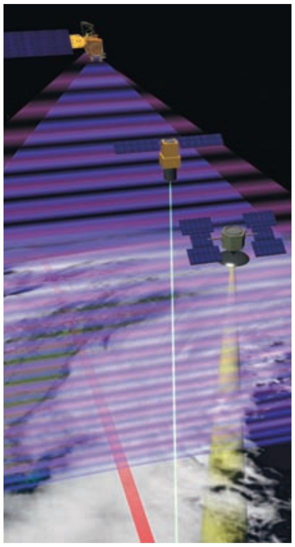


Figure 43: The "A-Train." This figure illustrates the constellation of satellites known as the "A-Train," which are making nearly contiguous observations of many facets of the Earth system. *Credit: NASA.*



physical and radiative properties. It flies in tight formation with the CALIPSO satellite, which was developed to provide new information about the effects of thin clouds and aerosols on changes in the Earth's climate. Global measurements of the three-dimensional distributions of aerosols and clouds will provide scientists with a more comprehensive data set that is essential for a better understanding of the Earth's climate forcings and feedbacks. The CALIPSO mission was implemented in collaboration with the French space agency, Centre National d'Etudes Spatiales. CloudSat and CALIPSO follow behind the Aqua satellite as part of the multi-satellite formation termed the "A-train" (see Figure 43 on the previous page). In addition to the EOS satellites Aura and Aqua, the "A-train" satellite formation includes the French satellite PARASOL, a mission designed to measure cloud and aerosol properties using polarization of reflected sunlight. The combination of these data with coincident measurements from Aqua and Aura will provide a rich source of information that can be used to assess the role of clouds in both weather and climate.

These activities will address Goals 12.1 and 12.5 of the CCSP Strategic Plan.

Solar Variability: Glory. The Glory mission will continue to be developed in FY 2007, and is planned to launch in 2008. It will carry a Total Irradiance Monitor (TIM) based on the SORCE TIM design, with the same high-precision phase-sensitive detection capability. Glory will also carry an Aerosol Polarimeter Sensor (APS), which will improve our ability to distinguish among aerosol types by measuring the polarization state of reflected sunlight. Both TIM and APS will provide key measurements beginning in 2008, the minimum of solar cycle 24. This less-active portion of the 11-year solar cycle is especially crucial in estimating any long-term trends in solar output—a key to understanding the 20th-century context of global change, as the Sun is the single entirely "external" forcing of the climate system that is unaffected by climate change itself (see <glory.giss.nasa.gov>).

These activities will address Goals 12.1 and 12.5 of the CCSP Strategic Plan.

Global Precipitation Measurement Mission. Motivated by the successes of the TRMM satellite and recognizing the need for a more comprehensive global precipitation measuring program, NASA and the Japan Aerospace Exploration Agency conceived a new Global Precipitation Measurement (GPM) Mission. A fundamental scientific goal of the GPM Mission is to make substantial improvements in global precipitation observations, especially in terms of measurement accuracy, sampling frequency, spatial resolution, and coverage, thus extending TRMM's rainfall time series. To achieve this goal, the mission will consist of a constellation of low-Earth-orbiting satellites carrying various passive and active microwave measuring instruments. The GPM Mission will be used to address important issues central to improving the predictions of climate, weather, and hydrometeorological processes, to stimulate operational forecasting, and to underwrite an effective public outreach and education program, including near-real-time dissemination of televised regional and global rainfall maps. Assessment of how natural and anthropogenic aerosols affect precipitation variability (and therefore the water cycle) is a complex and important problem. The capability to monitor the diurnal cycle of rainfall globally with GPM is expected to enable significantly improved understanding of the links between aerosols, climate variability, weather changes, hydrometeorological anomalies, and small-scale cloud macrophysics and microphysics.

These activities will address Goals 12.1 and 12.5 of the CCSP Strategic Plan.

Aquarius. Aquarius is a satellite mission to measure global sea surface salinity. Its instruments will measure changes in sea surface salinity over the global oceans to a precision of 2 parts in 10,000 (equivalent to about 1/6 of a teaspoon of salt in 1 gallon of water). By measuring global sea surface salinity with good spatial and temporal resolution, Aquarius will answer long-standing questions about how our oceans respond to climate change and the water cycle, including changes in freshwater input and output to the ocean associated with precipitation, evaporation, ice melting, and river runoff. Aquarius is a collaboration between NASA and the Argentine space agency with an expected launch date in 2009.

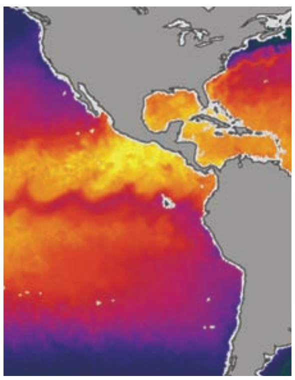
These activities will address Goals 12.1 and 12.5 of the CCSP Strategic Plan.

Ocean Surface Topography Mission.[5] The accurate, climate-quality record of sea surface topography measurements, started in 1992 with TOPEX/POSEIDON and continued in 2001 by the Jason satellite mission, will be extended with the Ocean Surface Topography Mission (OSTM). These missions have provided accurate estimates of regional sea-level change and of global sea-level rise unbiased by the uneven distribution of tide gauges. Ocean topography measurements from these missions have elucidated the role of tides in ocean mixing and maintaining deep ocean circulation. Further, quantitative determination of ocean heat storage from satellite measurements together with measurements from the global array of temperature/salinity profiling floats known as Argo have confirmed climate model predictions of the Earth's energy imbalance that is primarily due to greenhouse gas forcing. The high levels of absolute accuracy and cross-calibration make these missions uniquely suited for climate research. OSTM is a collaboration among NASA, NOAA, the French space agency CNES, and the European meteorological agency EUMETSAT, with a planned 2008 launch.

These activities will address Goals 12.1 and 12.5 of the CCSP Strategic Plan.

Orbiting Carbon Observatory. The Orbiting Carbon Observatory (OCO) is a new mission, expected to launch in 2008, that will provide the first dedicated, space-based measurements of atmospheric CO_2 (total column) with the precision, resolution, and coverage needed to characterize carbon sources and sinks on regional scales and to quantify their variability. Analyses of OCO data will regularly produce precise global maps of CO_2 in the Earth's atmosphere that will enable more reliable projections of future changes in the abundance and distribution of atmospheric CO_2 and studies of the effect that these changes may have on the Earth's climate.

These activities will address Goals 12.2 and 12.5 of the CCSP Strategic Plan.



Sea Surface Temperature. Both short-term numerical weather prediction and longer-term climate change detection require frequent, global sea surface temperature (SST) measurements at fine spatial resolution. Currently there are many different satellite-derived SST data sets available with varied product content, coverage, spatial resolution, timeliness, format, and accuracy. Recognizing that existing SST data products are less than ideal for numerical weather prediction and local- to global-scale climate change detection, the international Global Ocean Data Assimilation Experiment steering committee initiated a global high-resolution SST pilot project in 2000 to develop an operational demonstration system that will deliver a new generation of SST data products. These data products (10 km x 10 km and collected approximately every 6 hours) will be derived by combining readily available, complementary satellite and *in situ* observations in real-time to improve spatial coverage, temporal resolution, cross-sensor calibration stability, and SST product accuracy. The project will also generate, in delayed mode, higher quality SST data records that take advantage of additional data and techniques not available in near-real-time. The United States contributes significantly to this international collaboration by supporting the Global Data Assembly Center at the NASA Jet Propulsion Laboratory Physical Oceanography DAAC and the Long-Term Stewardship and Reanalysis Facility at the NOAA National Oceanographic Data Center, and by providing input data streams from its polar and geostationary satellite platforms. Information on the U.S. contributions to the high-resolution product can be found at <ghrsst.jpl.nasa.gov> and <ghrsst.nodc.noaa.gov>.

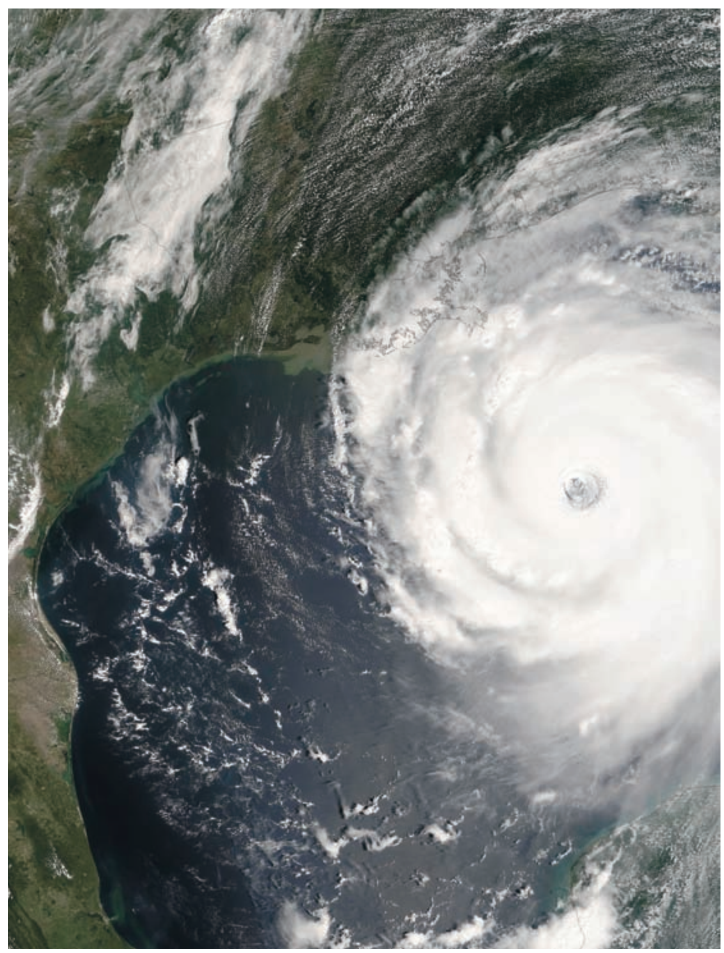
These activities will address Goals 12.1 and 12.5 of the CCSP Strategic Plan.

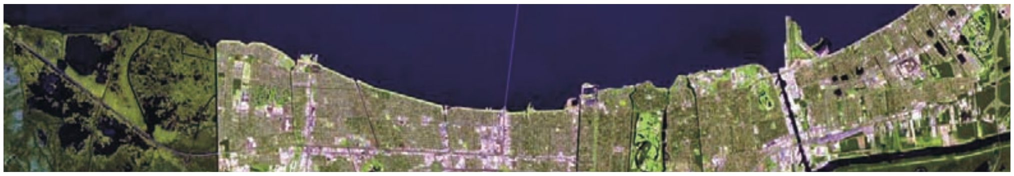
African Monsoon Multidisciplinary Analysis. African Monsoon Multidisciplinary Analysis (AMMA) is an international project to improve our knowledge and understanding of the West African Monsoon (WAM) and its variability, with an emphasis on daily-to-interannual time scales. AMMA is motivated by an interest in fundamental scientific issues and by the societal need for improved prediction of the WAM and its impacts on West African nations. U.S. involvement in AMMA will focus on climate, weather, and related aerosol issues associated with the African monsoon regions. A multidisciplinary field program combining long-term monitoring over several seasons with intensive observations occurred in the summer of 2006. The field measurements will be used to test and improve predictive models for the environment and climate of Africa, and for the impact of the monsoon on the global environment. U.S. participation in AMMA included ship, aircraft, and oceanographic sensors supported by multiple CCSP agencies. The ARM Mobile Facility described earlier in this chapter is conducting a year-long field campaign to study possible reasons for the ongoing drought in West Africa and the genesis of tropical waves that may evolve into hurricanes. In January 2006, the AMF, stationed at a site in Niamey, Niger, began sampling absorbing aerosols from desert dust in the dry season and deep convective clouds and large column moisture loadings during the summer monsoon. AMF will help provide better estimates of the Earth's radiation budget by combining cloud and aerosol measurements with those made by the Geostationary Earth Radiation Budget instrument on the European Union satellite. The AMMA work will continue into 2007 and build upon the results from the 2006 campaign as documented on the project web site, <amma-international.org>.

These activities will address Goals 12.2 and 12.3 of the CCSP Strategic Plan.

USGEO Near-Term Opportunity. USGEO was established in March 2005 as a standing subcommittee of the National Science and Technology Council Committee on Environmental and Natural Resources to replace the *ad hoc* Interagency Working Group on Earth Observations (IWGEO). USGEO has outlined a process for the development of a modern information management system, based on Federal Enterprise Architecture principles. The process follows contemporary commercial and academic practices for integrating distributed resources within a virtual organization framework based on a service-based architecture. It uses existing data management planning as its foundation, and relies heavily on an articulation of how data are used to drive the system design. USGEO is developing specific guidance to advance existing agency efforts that address the six "Near-Term Opportunities" outlined in the *USGEO Strategic Plan*: disaster warning, global land cover, sea level, drought, air quality, and enhanced data management (see <usgeo.gov>).

These activities will address Goals 12.6 and 13.3 of the CCSP Strategic Plan.

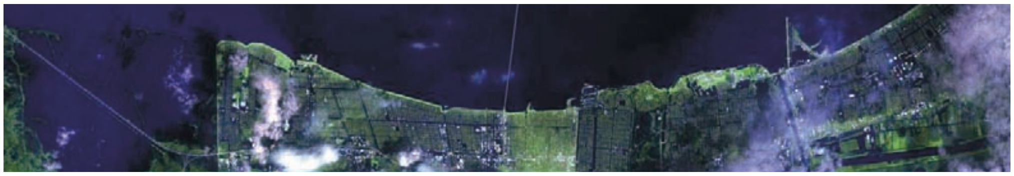


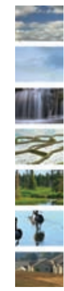


Data Fusion. As the length-of-record in the database of global observations increases, additional effort will be placed on assimilating Earth observations into GCMs, to produce an integrated view of the climate system and to better provide this view to users as part of decision-support and resource management systems. The value of the data itself will benefit by increased "data fusion" in which, for example, MODIS observations will be joined with the complementary capabilities of other Earth observing instruments, to provide much improved, more accurate and rigorous observations of key phenomena such as sea surface temperature, cloud characteristics, and land-surface features. Data fusion efforts will include instruments on existing EOS missions such as Terra, Aqua, ICESat, Aura, Landsat, and SORCE, and on recently launched missions such as CloudSat and CALIPSO and, farther in the future, Earth System Science Pathfinder missions and the GPM Mission. Such efforts will derive enhanced benefit from space-borne platforms flying in formation, along with instrumented aircraft and surface networks. Observations from the various systems will be co-registered in space and time, and made available to users in a unified format. For example, MODIS observations from the Terra and Aqua missions will be combined with similar observations to be obtained from the Visible Infrared Imaging Radiometer Suite (VIIRS) being developed for the NPOESS Preparatory Project, currently scheduled for launch in 2009, and NPOESS, currently scheduled for launch in 2013. Usefulness of the data fusion between two or more satellite data sets will depend upon the requirements of the application and the orbital characteristics (equatorial crossing time) of the satellites involved. This will enhance the Nation's imaging capability to observe land and atmosphere features on a global basis, providing a significant advance over capabilities provided for so many years by the venerable Advanced Very High Resolution Radiometer (AVHRR) that has flown successfully since 1981 on NOAA's operational satellite series. Efforts are being made to ensure the required data continuity. The fusion of space-borne observations together with air, ground, and ocean observations is crucial for gaining a better understanding of trends and associated consequences of the variability in the atmosphere-land-ocean system. This activity is closely related to the CCSP climate variability and change research element's priority of improving Earth system analysis capabilities.

These activities will address Goals 13.2 and 13.3 of the CCSP Strategic Plan.

Maintenance Needs. As new satellite instruments bring new measurement capabilities, a critical challenge is to maintain existing observing capabilities in areas of





importance to CCSP. For example, maintenance of the observational record of stratospheric ozone is essential to discern the nature and timing of projected ozone recovery. Other key variables requiring maintenance include radiative energy fluxes of the Sun and Earth, atmospheric CO_2 and methane concentrations, global surface temperature, and global land cover (e.g., as measured by Landsat).

The long-term record of global land cover was begun by Landsat 1 in 1972 and continues through the collection of data from Landsat 5 and Landsat 7. Landsat 7 was affected by a mechanical problem that occurred in May 2003. While Landsat 7 is still collecting seasonal global data sets, the data contain gaps in every scene (25% of each scene's pixels are missing along east/west edges). Techniques have been developed to partially compensate for the loss of data and Landsat 7 continues to provide usable data (see Figure 44). Landsat 5 continues to be a "workhorse" system for Earth observing studies. Launched in 1984, with a design life of 3 to 5 years, Landsat 5 continues to provide near-global data coverage, although the coverage is not amalgamated in the U. S. archive due to technical problems. A mechanical problem interrupted Landsat 5's operation in late 2005, but has since been corrected.

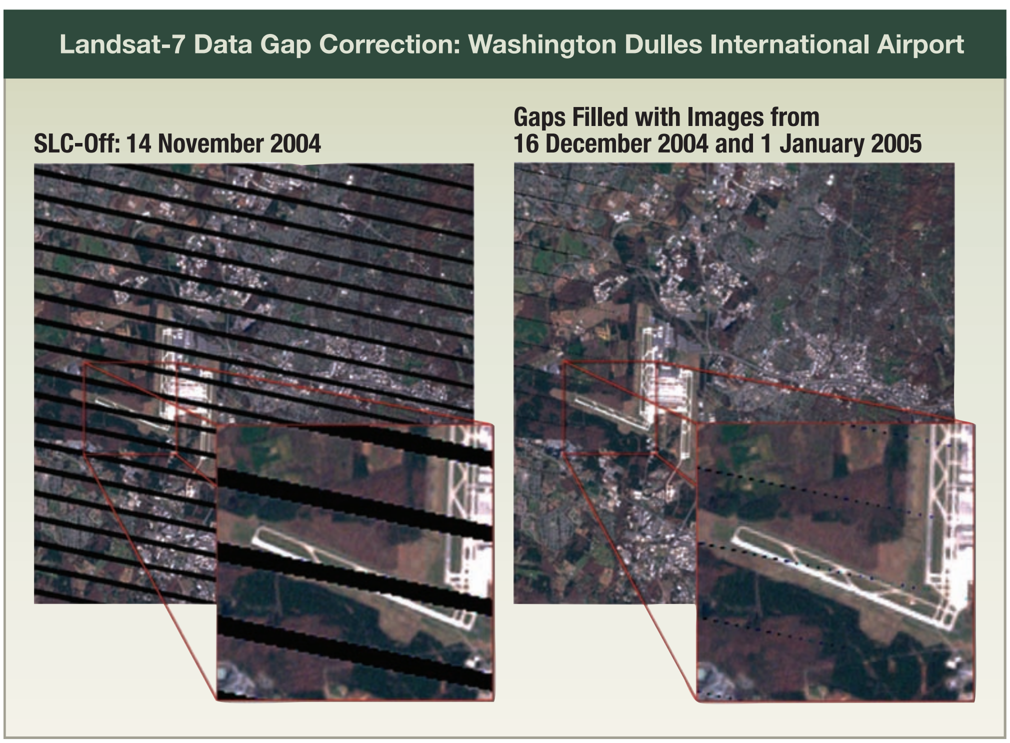


Figure 44: Landsat-7 Data Gap Correction: Washington Dulles International Airport. These products represent a portion of a false-color Landsat-7 scene over the Dulles airport area in Virginia, showing the gap-filled product developed to compensate for a mechanical problem on Landsat-7. *Credit: R. Beck, U.S. Geological Survey.*

Figure 45: Flooding in New Orleans due to Hurricane Katrina. Satellite observations can be used to provide frequent high-quality land-cover measurements in responding to rapid changes that occur during flooding and large-scale fires. This is graphically demonstrated by the comparison of two Landsat images showing areas of flooding in New Orleans due to Hurricane Katrina. *Credit: R. Beck, U.S. Geological Survey.*

Landsat 5 and Landsat 7 combined permit repeat coverage as frequently as every 8 days over ground-receiving station sites. Events such as Hurricane Katrina demonstrate the importance of frequent coverage, as shown in Figure 45. While scientists are looking to use other U.S. and international satellite instruments to provide interim land-cover data, there is a recognized need to ensure the continuing availability of high-quality land-cover measurements into the future. As such, Dr. John Marburger, the Director of the Office of Science and Technology Policy, formally outlined a series of near-term actions for DOC, DOD, DOI, and NASA on 23 December 2005. Dr. Marburger stated:

> "It remains the goal of the U.S. Government to transition the Landsat program from a series of independently planned missions to a sustained operational program funded and managed by a U.S. Government operational agency or agencies, international consortium, and/or commercial partnership. Concurrent with the actions cited above, the National Science and Technology Council—in coordination with NASA, DOI/USGS, and other agencies and offices of the Executive Office of the President, as appropriate—will lead an effort to develop a long-term plan to achieve technical, financial, and managerial stability for operational land imaging in accord with the goals and objectives of the U.S. Integrated Earth Observation System."

The record of precipitation that has been extended in recent years to include oceanic as well as land areas using measurements from TRMM is another example of a key climate data set that needs to be maintained and extended. These few examples of key climate variables are essential elements of the comprehensive observing system needed to monitor changes in the cycles of carbon, energy, water, and related biogeochemical processes that drive Earth's climate. Since the value of existing climate data sets greatly increases as the record is extended in time, it is imperative that existing observing capabilities be maintained and improved, while at the same time incorporating new requirements.

These activities will address Goals 12.3 and 12.6 of the CCSP Strategic Plan.

Development of a Climate Data Record Maturity Model. A combined effort between NOAA and NASA contributors to the OWG Data and Information Systems Subgroup has produced an initial form for a maturity model that appears to have excellent potential for combining multiple metrics into a framework for assessing and prioritizing climate data records. The maturity model has three basic axes:

- *Scientific Maturity*, related to uncertainty and capture of community understanding
- *Preservation Maturity*, related to managing the risk of data loss and cost effectiveness
- *Societal Benefit/Impact*, related to the value of the data and context for long-term use and data access.

The model suggests attributes for each axis and rankings for each attribute. By using the rankings, it is possible to develop consensus valuations of the maturity and potential value of a proposed climate data record, and thereby assist in decisions regarding archiving. The model was presented at several workshops during 2005 and early 2006, including the CCSP Workshop in Arlington and the Earth Science Information Partners Federation meeting in Washington, DC, in early January 2006. This model is also likely to be applied in NASA reviews of data products during 2007.

These activities will address Goal 13.3 of the CCSP Strategic Plan.

OBSERVING AND MONITORING THE CLIMATE SYSTEM CHAPTER REFERENCES

1) **ACIA**, 2005: *Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1042 pp.

2) **Chelton**, D.B., M.G. Schlax, M.H. Freilich, and R.F. Milliff, 2004: Satellite measurements reveal persistent small-scale features in ocean winds. *Science*, **303**, 978-983.

3) **Cheng**, M. and B.D. Tapley, 2004: Variations in the Earth's oblateness during the past 28 years. *Journal of Geophysical Research*, **109**, B09402, doi:10.1029/2004JB003028.

4) **Han**, S.-C., C.K. Shum, C. Jekeli, and D. Alsdorf, 2005: Improved estimation of terrestrial water storage changes from GRACE. *Geophysical Research Letters*, **32**, L07302, doi:10.1029/2005GL022382.

5) **Hansen**, J., L. Nazarenko, R. Ruedy, M. Sato, J. Wiollis, A. Del Genio, D. Koch, A. Lacis, K. Lo, S. Menon, T. Novakov, J. Perlwitz, G. Russell, G.A. Schmidt, and N. Tausnev, 2005: Earth's energy imbalance: Confirmation and implications. *Science*, **308**, 1431-1435.

6) **Nghiem**, S.V., K. Steffen, G. Neumann, and R. Huff, 2005: Mapping of ice layer extent and snow accumulation in the percolation zone of the Greenland ice sheet. *Journal of Geophysical Research*, **110**, F02017, doi:10.1029/2004JF000234.

7) **Parkinson**, C. L. and D. J. Cavalieri, 2002: A 21-year record of Arctic sea-ice extents and their regional, seasonal and monthly variability and trends. *Annals of Glaciology*, **34**, 441-446.

8) **Tapley**, B.D., S. Bettadpur, J.C. Ries, P.F. Thompson, and M.M. Watkins, 2004: GRACE measurements of mass variability in the Earth system. *Science*, **305**, 503-505.