OUR CHANGING PLANET

The U.S. Climate Change Science Program for Fiscal Year 2007

A Report by the
Climate Change Science Program and
the Subcommittee on Global Change Research

A Supplement to the President's Budget for Fiscal Year 2007

Climate Change Science Program and Subcommittee on Global Change Research

This document describes the U.S. Climate Change Science Program (CCSP) for FY 2007. It provides a summary of the achievements of the program, an analysis of the progress made, and budgetary information. It thereby responds to the annual reporting requirements of the U.S. Global Change Research Act of 1990 (section 102, P. L. 101-606). It does not express any regulatory policies of the United States or any of its agencies, or make any findings of fact that could serve as predicates for regulatory action. Agencies must comply with required statutory and regulatory processes before they could rely on any statements in this document or by the CCSP as a basis for regulatory action.

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November 2006

Members of Congress:

We are pleased to transmit a copy of *Our Changing Planet: The U.S. Climate Change Science Program for Fiscal Year 2007*. The report describes the activities and plans of the Climate Change Science Program (CCSP), which incorporates the U.S. Global Change Research Program, established under the Global Change Research Act of 1990, and the Climate Change Research Initiative, established by the President in 2001. CCSP coordinates and integrates scientific research on climate and global change supported by 13 participating departments and agencies of the U.S. Government.

This Fiscal Year 2007 edition of *Our Changing Planet* highlights recent advances supported by CCSP-participating agencies in each of the program's research and observational elements, as called for in the *Strategic Plan for the U.S. Climate Change Science Program* released in July 2003. An addition to the report includes an analysis of the significant progress that CCSP has made toward its overarching goals since the release of the *Strategic Plan*.

The document describes a wide range of new and emerging observational capabilities which, combined with the program's analytical work, are leading to remarkable advances in understanding the underlying processes responsible for climate variability and change. It illustrates advances in U.S. modeling capabilities to represent past, present, and potential future changes in the physical and biological dimensions of the Earth system. The report also highlights progress being made to explore the uses and limitations of evolving knowledge to manage risks and opportunities related to climate variability and change. The final chapter documents the program's numerous current activities to promote cooperation between the U.S. scientific community and its worldwide counterparts.

The document also outlines how CCSP plans to continue implementation of the *Strategic Plan* during FY 2007. The program will continue to emphasize work on 21 scientific synthesis and assessment reports. The first of these, *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*, was released in April of this year and answers a set of key questions related to ongoing observations of the Earth's temperature.

CCSP is committed to its mission to facilitate the creation and application of knowledge of the Earth's global environment through research, observations, decision support, and communication. We thank the CCSP-participating agencies for their close cooperation, and we look forward to working with Congress in the continued development of this important program.

Carlos M. Gutierrez

Secretary of Commerce

Chair, Committee on Climate Change Science and Technology Integration

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Secretary of Energy

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THE U.S. CLIMATE CHANGE SCIENCE PROGRAM

THE U.S. CLIMATE CHANGE SCIENCE PROGRAM FOR FY 2007

Many aspects of the environment and society are significantly affected by climate. The Climate Change Science Program (CCSP) was established in 2002 to empower the Nation and the global community with the science-based knowledge to manage risks and opportunities of change in the climate and related environmental systems. CCSP incorporates and integrates the U.S. Global Change Research Program (USGCRP) with the Administration's U.S. Climate Change Research Initiative (CCRI).

The USGCRP was established by the Global Change Research Act of 1990 to enhance understanding of natural and human-induced changes in the Earth's global environmental system; to monitor, understand, and predict global change; and to provide a sound scientific basis for national and international decisionmaking.

The Earth has always experienced climate variations at time scales ranging from seasons to millions of years. With the likelihood of a recent and growing human influence on climate, it is vital for society to be equipped with the best possible knowledge of climate variability and change so that we may exercise responsible stewardship for the environment, lessen the potential for negative climate impacts, and take advantage of positive opportunities where they exist. The importance of these issues and the unique role that science can play in informing society's responses give rise to CCSP's guiding vision.

CCSP GUIDING VISION

A nation and the global community empowered with the science-based knowledge to manage the risks and opportunities of change in the climate and related environmental systems.

Research conducted through CCSP is building on scientific advances of the last few decades and is deepening our understanding of the interplay of natural and human-caused forces. CCSP is developing information to facilitate comparative analysis of different approaches to adaptation to and mitigation of climate change. CCSP also promotes capacity development among scientists and information users—both in the developed and the developing world—to address the interactions between climate change, society, and the environment.

CCSP MISSION

Facilitate the creation and application of knowledge of the Earth's global environment through research, observations, decision support, and communication.

Integrating Climate and Global Change Research

CCSP integrates the USGCRP, which was mandated by Congress in the Global Change Research Act of 1990 (P.L. 101-606, 104 Stat. 3096-3104), and the CCRI, which was established by President Bush in 2001, to improve understanding of uncertainties in climate science, expand global observing systems, develop science-based resources to support policymaking and resource management, and communicate findings broadly among scientific and stakeholder communities. Thirteen departments and agencies of the U.S. Government participate in CCSP, including:

- Department of Agriculture (USDA)
- Department of Commerce / National Oceanic and Atmospheric Administration (DOC/NOAA)
- Department of Defense (DOD)
- Department of Energy (DOE)
- Department of Health and Human Services (HHS)
- Department of the Interior / U.S. Geological Survey (DOI/USGS)
- Department of State (DOS)
- Department of Transportation (DOT)
- Agency for International Development (USAID)
- Environmental Protection Agency (EPA)
- National Aeronautics and Space Administration (NASA)
- National Science Foundation (NSF)
- Smithsonian Institution (SI).

DEFINITION OF KEY TERMS

Adaptation
Adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects.

Climate
The statistical description of the mean and variability of relevant measures of the atmosphere-ocean system over periods of time ranging from weeks to thousands or millions of years.

Climate Change
A statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or to external forcing, including changes in solar radiation and volcanic eruptions, or persistent human-induced changes in atmospheric composition or in land use.

Climate Feedback
An interaction among processes in the climate system in which a change in one process triggers a secondary process that influences the first one. A positive feedback intensifies the change in the original process, and a negative feedback reduces it.

Climate Forcing
A process that directly changes the average energy balance of the Earth-atmosphere system by affecting the balance between incoming solar radiation and outgoing or "back" radiation. A positive forcing tends to warm the surface of the Earth and a negative forcing tends to cool the surface.

Climate System
The highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface, the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations, and human-induced forcings such as the changing composition of the atmosphere and land-use change.

Climate Variability
Variations in the mean state and other statistics of climatic features on temporal and spatial scales beyond those of individual weather events. These often are due to internal processes within the climate system. Examples of cyclical forms of climate variability include the El Niño Southern Oscillation, the North Atlantic Oscillation, and the Pacific Decadal Oscillation.

Decision-Support Resources
The set of observations, analyses, interdisciplinary research products, communication mechanisms, and operational services that provide timely and useful information to address questions confronting policymakers, resource managers, and other users.

Global Change
Changes in the global environment (including alterations in climate, land productivity, oceans or other water resources, atmospheric chemistry, and ecological systems) that may alter the capacity of the Earth to sustain life (from the Global Change Research Act of 1990, PL 101-606).

Mitigation
An intervention to reduce the human-induced factors that contribute to climate change. This could include approaches devised to reduce emissions of greenhouse gases to the atmosphere; to enhance their removal from the atmosphere through storage in geological formations, soils, biomass, or the ocean; or to alter incoming solar radiation through several "geo-engineering" options.

Observations
Standardized measurements (either continuing or episodic) of variables in climate and related systems.

Prediction
A probabilistic description or forecast of a future climate outcome based on observations of past and current climatological conditions and quantitative models of climate processes (e.g., a prediction of an El Niño event).

Projection
A description of the response of the climate system to an assumed level of future radiative forcing. Changes in radiative forcing may be due to either natural sources (e.g., volcanic emissions) or human-induced factors (e.g., emissions of greenhouse gases and aerosols, or changes in land use and land cover). Climate "projections" are distinguished from climate "predictions" in order to emphasize that climate projections depend on scenarios of future socioeconomic, technological, and policy developments that may or may not be realized.

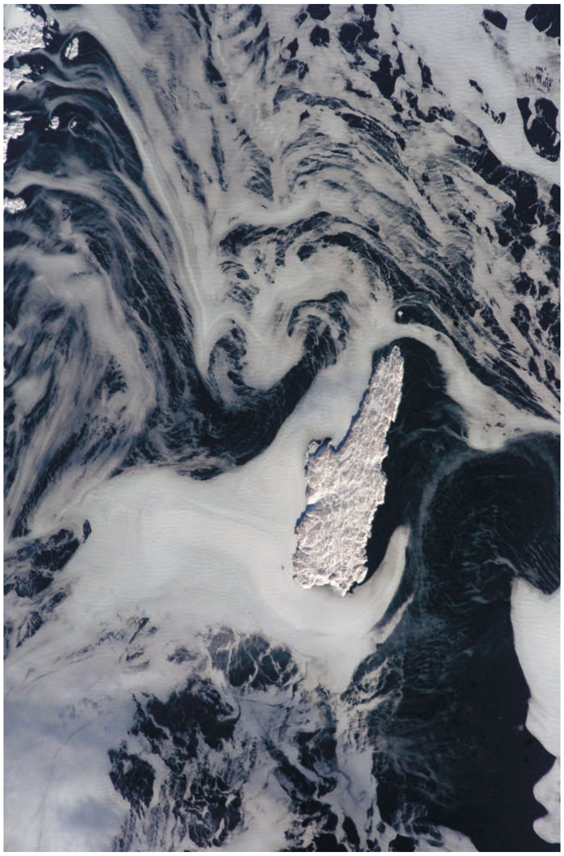
Weather
The specific condition of the atmosphere at a particular place and time, measured in terms of variables such as wind, temperature, humidity, atmospheric pressure, cloudiness, and precipitation.

In addition, the Executive Office of the President and other related programs have designated liaisons who participate on the CCSP Interagency Committee, including:

- Office of Science and Technology Policy (OSTP)
- Council on Environmental Quality (CEQ)
- Office of Management and Budget (OMB)
- Climate Change Technology Program (CCTP)
- Office of the Federal Coordinator for Meteorology (OFCM)
- National Institute of Standards and Technology (NIST).

Appendix A, "The Climate Change Science Program Participating Agencies," contains information about the specific missions and roles of each agency participating in CCSP. Appendix B, "Climate Change Science Program FY 2007 Budget Tables," in the insert pocket, contains budgetary analyses of the program grouped by agency as well as a program-wide interagency cross-cut grouped by the strategic goals and research elements of CCSP as described in the *Strategic Plan for the U.S. Climate Change Research Program* published in July 2003.

As a multi-agency program, CCSP harnesses the unique approaches and missions of its participating agencies to encourage research that leads to expanded and new results. A significant challenge that arises from working across many agencies is integrating climate and global change research to develop a comprehensive view of climate change and its potential significance. CCSP adds value to the individual Earth and climate science missions of its 13 participating agencies and their national and international partners by coordinating research and facilitating integration of information to achieve results that no single agency, or small group of agencies, could attain.



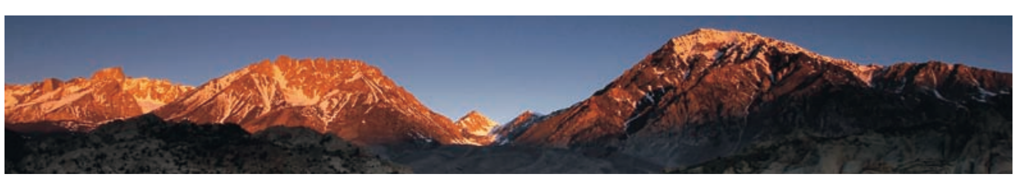
CCSP relies not only on the agency programs stated in its budget cross-cut, but also on agency activities that are not formally included in the CCSP budget. Examples of these directly related activities are NOAA's long-term surface, balloon, and satellite-based meteorological observations; surface hydrologic and satellite land-cover observations from USGS; and future satellite measurement programs including the tri-agency (NOAA, DOD, NASA) National Polar-Orbiting Operational Environmental Satellite System (NPOESS); and the planned implementation of a Landsat data continuity mission. Without input from activities such as these, CCSP would be unable to fulfill its mission.

CCSP also relies on and provides input to other major interagency programs that observe and study particular aspects of the environment and associated human activities. Foremost among these is the CCTP, which develops and studies technological options for responding to climate change. A key observational linkage is with the U.S. Integrated Earth Observation System, which is part of the international Global Earth Observation System of Systems (GEOSS). CCSP is also linked to another set of activities articulated in the *U.S. Ocean Action Plan* (see <www.ocean.ceq.gov/actionplan.pdf>) and being planned by the Joint Subcommittee on Ocean Science and Technology. Connections to programs such as these allow CCSP and its partners to leverage their resources to derive mutual benefits from advances in any one program.

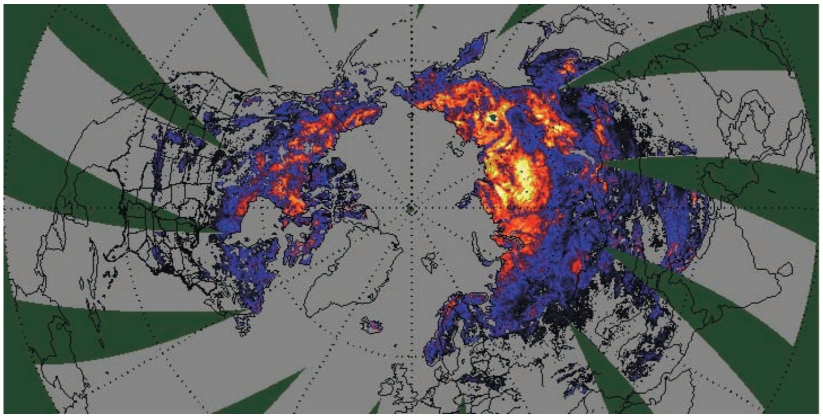
Program Management

As described in the *CCSP Strategic Plan*, CCSP employs a management approach that integrates the planning and implementation of individual climate and global change research programs of the participating Federal agencies and departments to reduce overlaps, identify and fill programmatic gaps, and synthesize products and deliverables generated under the auspices of CCSP. Five mechanisms are used to achieve this management approach:

- *Executive Direction* – The Interagency Working Group on Climate Change Science and Technology and the CCSP Principals Committee are responsible for overall priority setting, program direction, management review, and accountability to deliver program goals.
- *Agency Implementation* – CCSP-participating departments and agencies are responsible for conducting research, developing modeling tools, developing and operating observing systems, and producing CCSP-required products, often in collaboration with interagency working groups.
- *Interagency Planning and Implementation* – Several interagency working groups, including one for each CCSP research element, are responsible for coordinating planning and implementation to align agency programs with CCSP priorities.
- *External Guidance and Interaction* – External advisory groups and organizations, including the National Academies, provide external guidance, oversight, and interactions to ensure scientific excellence, credibility, and utility.
- *Program Support* – The CCSP Office provides staffing and day-to-day coordination of CCSP-wide program integration, strategic planning, product development, and communications.



Coordinating Research Elements



Efforts to foster integration occur on many levels. One is improving coordination of scientific research and the flow of information through interdisciplinary and interagency working groups focused on each of seven main research elements of the program plus a number of cross-cutting activities or themes. CCSP's research elements include atmospheric composition, climate variability and change, the global water cycle, land-use and land-cover change, the global carbon cycle, ecosystems, and human contributions and responses to environmental change. For each of the research elements, recent highlights and program plans for FY 2007 are described in subsequent chapters of this report. The budget tables appendix contains information on the CCSP budget by research element. This budget cross-cut illustrates integrative management of the program that starts from research-driven requirements and extends to coordinated planning to distribute and integrate work efficiently across CCSP's participating agencies.

Integrating research and observational approaches across disciplinary boundaries is essential for understanding how the Earth system functions and how it will change in response to future forcing. This is due to the interconnectedness among components of the Earth system, which often relate to each other through feedback loops. Interdisciplinary interactions in CCSP are scaled to the nature of the problem. In some cases, the necessary science may be conducted within a small set of disciplines, such as those required to improve understanding of cloud microphysics. In other cases, highly interdisciplinary approaches are required, such as in the case of making projections about the future state of the Earth system and analyzing their implications. In the latter example, expertise ranging from the social sciences to atmospheric dynamics and chemistry to oceanography to the biological sciences is required.

Interdisciplinary research is only one aspect of the integration facilitated by CCSP. Integration in CCSP also refers to the steps being taken to create more seamless approaches between the theory, modeling, observations, and applications that are required to address the multiple scientific challenges being confronted by CCSP. Finally, integration in CCSP also refers to the enhancement of cooperation across agencies toward meeting the objectives articulated in the *CCSP Strategic Plan*.

Integrated Program Analysis

In a highly distributed program such as CCSP, it is often a challenge to develop and maintain a cohesive perspective, ensuring that key components or interactions of the integrated Earth system are not overlooked. To help address this challenge, the program has often sought guidance from the National Academies. CCSP has recently requested that the National Research Council (NRC) establish a new committee to provide high-level integrated advice on the evolution of the program. The committee will provide independent advice, through annual reports, on the strategy and evolution of CCSP. Specific topics the committee will address in its first two annual reports include:

- Evaluation of progress toward program goals. The *CCSP Strategic Plan* and the guidelines given in the 2005 NRC report *Thinking Strategically: The Appropriate Use of Metrics for the Climate Change Science Program* will provide a starting point for this examination. The committee will prepare a report that provides findings and recommendations on the process for evaluating progress toward the five CCSP goals and a preliminary assessment of progress to date.
- The committee will examine the program elements described in the *CCSP Strategic Plan* and identify priorities to guide the future evolution of the program in the context of established scientific and societal objectives. These priorities may include adjustments to the balance between science and applications, shifts in emphasis given to the various scientific themes, and identification of program elements not supported in the past.

CCSP will continue to rely on other mechanisms for scientific guidance and advice, including other NRC committees that focus on particular components of the climate system (e.g., the Climate Research Committee and the Committee on the Human Dimensions of Global Change). CCSP will also continue to utilize scientific advisory groups that support individual agencies, scientific steering groups organized to coordinate different CCSP research elements, and open dialog with the domestic and international scientific and user communities interested in global change issues.

Analysis of Progress Toward Goals

The CCSP has five overarching goals that cut across the program's research elements, providing an integrated analytical framework. These five goals span the full range of climate-related issues, including natural climate conditions and variability; forces that influence climate, including cycles and processes that affect atmospheric concentrations of greenhouse gases and aerosols; climate responses; consequences for ecosystems, society, and the economy; and application of knowledge to decisionmaking. These

CCSP GOALS

Goal 1: Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change.

Goal 2: Improve quantification of the forces bringing about changes in the Earth's climate and related systems.

Goal 3: Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future.

Goal 4: Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes.

Goal 5: Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.

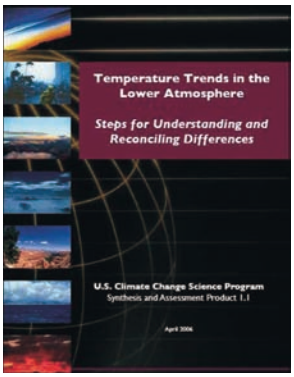
overarching goals are complemented by the detailed objectives, milestones, products, and payoffs articulated in the *CCSP Strategic Plan*.

This section of *Our Changing Planet*, which is new this year, provides an overview of progress made toward the program's goals since the release of the *CCSP Strategic Plan* in 2003. Because of the program's breadth and wide-ranging progress, this overview cannot address all advances. In addition, this section does not purport to provide a thorough assessment of climate change or the extent of the scientific uncertainties that remain. Instead, it provides examples that illustrate the scope and significance of the progress that CCSP has made in expanding and applying understanding of climate. See pages 157 to 163 for a description of the 21 CCSP synthesis and assessment products.

U.S. climate research has historically focused on Goals 1 through 3, which emphasize improvements in fundamental understanding of the climate system, its driving forces, and the tools to make predictions of short-term climate variability and potential long-term climate change more reliable. As the science has matured and its societal utility has become more evident, the importance of Goals 4 and 5 has become magnified. The examples of progress provided below are often the result of activities that integrate research from many disciplines conducted or supported across the participating agencies.

Goal 1: Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change.

The program's research is built upon a solid foundation of observationally based analyses, which are used to improve understanding of Earth system processes, to test and improve models, and to determine the extent of climate variations. These analyses span all aspects of the climate system. In the past few years, these analyses have enabled several important advances in understanding the nature and variability of the Earth system.



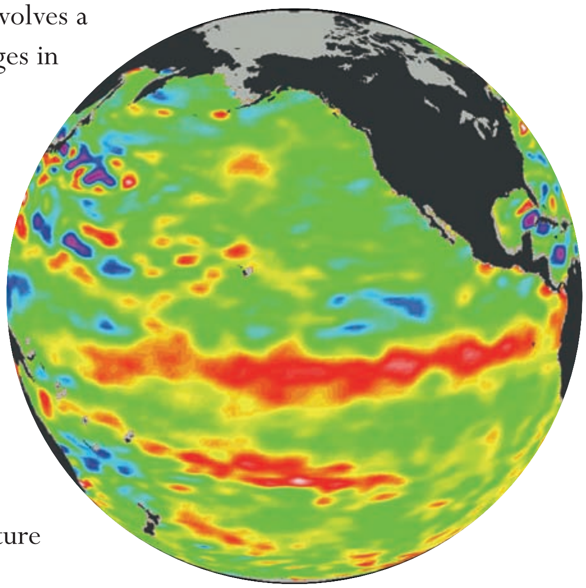
A key example is the analytical work reported in the CCSP synthesis and assessment report *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences* (CCSP, 2006). Previously reported discrepancies between the amount of warming near the surface and higher in the atmosphere have been used to challenge the reliability of climate models and the reality of human-induced global warming. Specifically, surface data showed substantial global-average warming, while early versions of satellite and radiosonde data showed little or no warming above the surface. This significant discrepancy no longer exists because errors in the satellite and radiosonde data have been identified and corrected. New data sets have also been developed that do not show such discrepancies.

The synthesis and assessment report is an important revision to the conclusions of earlier reports from the NRC (2000) and the Intergovernmental Panel on Climate Change (IPCC, 2001). For recent decades, all current atmospheric data sets now show global-average warming that is similar to the surface warming. While these data are consistent with the results from climate models at the global scale, discrepancies in the tropics remain to be resolved. Nevertheless, the most recent observational and model evidence has increased confidence in our understanding of observed climatic changes and their causes.

While temperature has traditionally been a leading measure of climate variability and change, CCSP's work on other climate system parameters has significantly advanced understanding of variations that have important connections to societal well-being. Prime illustrations of this work are recent wide-ranging analyses of the terrestrial and oceanic water cycle. For example, observations in the western United States indicate that the annual peak in spring river runoff is occurring earlier in the season and is supplying less water during the growing season (Mote *et al.*, 2005). New satellite-based observations of the polar regions indicate significant reductions in the volume of the Greenland Ice Sheet (Velicogna and Wahr, 2005), declining Arctic sea-ice cover, and loss of ice mass in Antarctica despite no measurable change in snowfall over the last 50 years (Velicogna and Wahr, 2006; Managhan *et al.*, 2006). Observations of global sea-level increases are consistent with the declining volume of land ice as well as observations of ocean warming, which contributes to sea-level rise by expanding ocean volume. Observations of the North Atlantic indicate a reduction in salinity (Curry and Mauritzen, 2005), which climate system models indicate may lead to a slowdown of the large-scale ocean circulation that transports heat to high-latitude regions (Stouffer *et al.*, 2006a). Global-scale observations of ocean temperature indicate a pattern of warming that is generally consistent with climate model projections of greenhouse warming (Barnett *et al.*, 2005a). Although significant uncertainty remains, a pattern of climatic change is emerging that appears to be the likely result of a human imprint upon a complex background of natural climate system variability (Barnett *et al.*, 2005b; NRC, 2001).

Although it is scientifically critical to observe and understand variations in the average state of particular climate parameters, it is perhaps even more important for society to understand changes in the frequency or intensity of relatively uncommon phenomena (extreme events). One example of research on this topic indicates that recent U.S. droughts are relatively minor in comparison to naturally occurring droughts over the past millennium as shown by proxy records derived from tree rings and sediment cores (Cook *et al.*, 2004). Other examples of research on extreme events are observational analyses suggesting that the occurrence of severe hurricanes is increasing (Emanuel, 2005; Webster *et al.*, 2005) and opposing analyses suggesting that the apparent trends may be the result of flaws in the observational data (Landsea *et al.*, 2006). Interpreting changes in the characteristics of extreme events remains one of CCSP's ongoing research frontiers.

Under Goal 1, CCSP has made important progress in understanding the climate system's natural recurrent patterns of variability. The most prominent is El Niño, which recurs on a time scale of approximately 2 to 7 years and involves a warming of the eastern tropical Pacific in combination with changes in atmospheric circulation. Recent research links decadal changes in this pattern to droughts and wet conditions over North America and suggests that a portion of such decadal changes may be predictable (Seager *et al.*, 2005). Other important sets of recurrent patterns of variability include the so-called Annular Modes, which are concentric patterns of high and low pressure centered on the North and South Poles. Recent research has made significant advances in explaining the nature of these patterns and their effect on mid-latitude climate (Thompson and Wallace, 2000). Using this improved understanding of natural climate variability to improve predictions of the occurrence of specific climate variations from 2 weeks to several years in the future remains a major challenge.



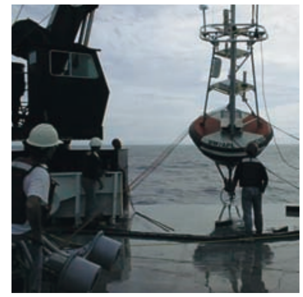
Goal 2: Improve quantification of the forces bringing about changes in the Earth's climate and related systems.

An understanding of the factors responsible for global environmental change is necessary to make long-term climate projections. These forcing factors include greenhouse gases, tiny airborne particles (aerosols), land cover, and solar variability.

The greenhouse gas that plays the largest role in causing climate change is carbon dioxide (CO_2). An understanding of the sources and sinks of CO_2 and of carbon cycle dynamics is required for developing scenarios of future atmospheric CO_2 concentration and for developing effective strategies to manage carbon cycle processes that affect the concentration of atmospheric CO_2.

Climate and the global carbon cycle are a tightly coupled system where changes in climate affect the transfer of atmospheric CO_2 to the terrestrial biosphere and the ocean, and *vice versa*. An important conclusion of recent carbon cycle research is that future warming is likely to lead to a further decrease in the efficiencies of land and ocean in absorbing excess CO_2 (i.e., a positive feedback) (Fung *et al*., 2005). This assessment is based on advances in U.S. and global carbon observations and improvements in carbon cycle models. Controlled experiments on carbon uptake and release in ecosystems are one means of improving our understanding of carbon cycle dynamics, which can contribute to corresponding carbon cycle model improvements. For example, Free-Air Carbon Dioxide Enrichment experiments, in which CO_2 is purposely injected into the air around a small plot of land, have led to the conclusion that the mass of carbon in ecosystems initially tends to increase when exposed to increased levels of CO_2 (Norby *et al*., 2005; Jastrow *et al*., 2005). This increase may be limited by the availability of nutrients, although a comprehensive meta-analysis indicates that nitrogen supply generally keeps pace with plant demands in natural systems (Luo *et al*., 2006). Other controlled experiments in which ecosystems are purposely warmed generally indicate greater ecosystem CO_2 release with higher temperatures. However, there are still significant uncertainties associated with the biospheric response to climate change, particularly with respect to the complex and dynamic nature of ecosystems and their interactions with climate and the hydrologic cycle.

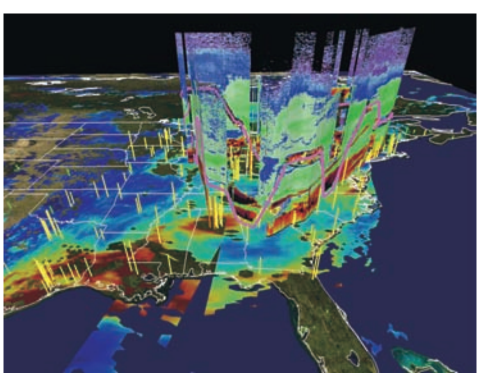
Another important recent advance is improved estimates of the amount of carbon being sequestered in North America and globally, and in particular, how the rate of carbon uptake is changing in all ecosystems. These estimates are made through the innovative combination of carbon cycle models and observations of carbon concentrations and isotopes (Fung *et al.*, 2005). A key goal of the North American Carbon Program is to further improve estimates of carbon sources and sinks. Work of this nature is vital for assessing the efficacy of natural carbon uptake, as well as the potential for purposeful carbon capture in managed ecosystems.



Observations of ocean carbon are important for addressing uncertainties associated with the global carbon budget. New global-scale ocean carbon analyses indicate increasing carbon concentrations in ocean water. In addition to confirming the oceans as a significant carbon sink, this information is also being used to estimate the increase in ocean acidity caused by increasing amounts of dissolved CO_2, and the potentially deleterious consequences for marine ecosystems (Orr *et al.*, 2005). Recent measurements of carbon sedimentation along continental shelves have shown these regions to be responsible for a significant fraction of oceanic carbon uptake (Muller-Karger *et al.*, 2005).

CCSP has made significant advances in understanding the processes responsible for the production and destruction of other greenhouse gases, including methane and nitrous oxide. For example, recent analyses estimate that approximately 60% of all methane emissions from wetlands occur in the tropics (Melack *et al.*, 2004). In polar regions, recent studies have elucidated processes by which carbon, currently trapped either as organic matter or methane hydrates in the permafrost (frozen soil), is released to the atmosphere (Zimov *et al.*, 2006). Warming increases these releases and can create an amplifying feedback loop. Another example of progress on non-carbon greenhouse gases is the work that has improved understanding of interactions between climate variability and near-surface ozone, which is a health hazard.

One of the largest uncertainties in projections of potential future climate change is the role of aerosols. Recent research has reduced some of this uncertainty, in part through efforts made possible by the CCRI. In the first phase of preparing the synthesis and assessment report that deals with aerosol properties and their impacts on climate, a comprehensive paper has been published that reviews recent progress in characterizing aerosols and assessing the direct effect of aerosols on climate change (Yu *et al.*, 2006). This work will serve as a major resource in the preparation of the IPCC Fourth Assessment Report. One study cited in the review paper, for example, concluded from



observational evidence that enhanced aerosol concentrations increase the amount of thermal energy emitted by Arctic clouds to the surface, which could augment surface warming caused by greenhouse gases (Lubin and Vogelmann, 2006).

Examples of other areas in which the program has made significant advances in understanding include the potential effects of land-use change on climate, the recovery of the ozone layer and its interactions with climate change, and the magnitude of variations in solar output and their potential effects on climate (Feddema *et al.*, 2005; Reinsel *et al.*, 2005; Lean *et al.*, 2005; Meehl *et al.*; 2004a).

Goal 3: Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future.

CCSP has significantly advanced the ability to estimate future Earth system conditions at time scales ranging from months to centuries and at spatial scales ranging from regional to global. The primary tools for Earth system prediction and projection are computer models that reflect the best available knowledge of Earth system processes. Recent model simulations of the climate of the past 100 years have been compared to observations. The results generally indicate improvements over previous generations of models, including the ability to represent weather systems, climate variability (e.g., monsoons, El Niño), ocean processes (e.g., the Gulf Stream), surface hydrology, and other Earth system processes, components, and dynamics (Collins *et al.*, 2006; Schmidt *et al.*, 2006). One of the ways in which these models have advanced is through improvements in the representation of the processes responsible for key Earth system feedbacks such as those associated with water vapor, clouds, sea ice, and the carbon cycle (Delworth *et al.*, 2006; Gnanadesikan *et al.*, 2006; Wittenberg *et al.*, 2006).

The magnitude of future warming will be strongly influenced by the extent to which atmospheric water vapor concentration increases in response to an initial warming caused by increases in CO_2 and other greenhouse gases. An accurate representation of this feedback in climate models is critical for making long-term climate projections. Recent innovative analyses have shown that water vapor increases in the upper atmosphere measured by satellites and balloon-borne sensors are generally consistent with state-of-the-art climate model simulations, lending credence to the ability of current models to represent the water vapor feedback (Soden *et al.*, 2005; Cess, 2005).

New cloud simulation modules that have been developed and incorporated into climate system models indicate improved performance when compared to the ability of earlier cloud modules to represent day-to-day and seasonal cloud

variability (Khairoutdinov *et al.*, 2005). Advances have also been made in understanding the effects of aerosols on cloud formation and precipitation, although significant uncertainties remain (Lohmann and Feicher, 2005). Other types of important cloud processes that require further work are those associated with deep convection (thunderstorms), low-level ocean stratus cloud formation, and the very fine-scale effects of cloud properties on the Earth's energy balance (Stephens, 2005). A priority for the program is to continue to improve understanding of these and other cloud processes and to incorporate these improvements into climate models.

The CCSP modeling strategy utilizes a multi-tiered approach in which new and improved Earth system sub-models (e.g., clouds, ecosystem dynamics, sea ice) are developed and tested by individual researchers or small research teams. When significant improvements in these sub-models arise, they are integrated as appropriate into high-end Earth system models. A result of these ongoing efforts is a set of U.S. models that expand beyond earlier atmosphere-ocean models to include relatively sophisticated representations of land-surface hydrology, sea ice, ecosystems, and atmospheric chemistry. Several U.S. Earth system modeling centers have used variations of these models to produce ensembles of projections that are providing important new perspectives on potential future climate system change (Meehl *et al.*, 2004a; Stouffer *et al.*, 2006b). These ensembles are also being used to characterize the intrinsic uncertainty associated with potential future climate change.

A set of new high-resolution climate model simulations has been completed for North America that provides information at a scale finer than 100 km x 100 km (Leung *et al.*, 2004; Han and Roads, 2004; Mason, 2004; Wood *et al.*, 2004). The ability of these regional-scale models to represent climate processes is being assessed (see <www.narccap.ucar.edu>). These regional and global simulations, based on models developed at U.S. institutions, are contributing to the IPCC Fourth Assessment Report.

Because Earth system models are extremely complex and benefit greatly from input and evaluation by multiple research teams, several new efforts have been initiated to enable sharing, testing, and improvement of these models by diverse groups of researchers (Meehl *et al.*, 2004b, 2005). Many of the recent model simulations referred to above are now widely available through a new capability for data archiving and dissemination developed by the Program for Climate Model Data and Intercomparison (see <www-pcmdi.llnl.gov>). Large strides have been made in creating climate model code according to a set of standards that facilitate exchange of sub-models (e.g., the Earth System Model Framework), which enables researchers to readily trace the source of differences between various models and between models and observations. The U.S. Climate Variability and Predictability Program (CLIVAR) is exploring a new approach for bringing together observers, theorists, and high-end modelers to improve key model deficiencies (Bretherton *et al.*, 2004; USCLIVAR, 2002). This approach is attempting to significantly reduce the time lags that often exist between the observation of key climate processes and the integration of these processes into more comprehensive Earth system models. Several high-end Earth system modeling efforts in the United States, which involve many different, independent research teams, are using these types of new collaborative approaches and tools to evaluate, improve, and integrate model components.

Goal 4: Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes.

CCSP has made significant advances in understanding the potential impacts of climate change. One of the hallmarks of CCSP research is the use of many different sources of information, including analyses using prehistoric information, direct observations, and model-based projections. Recent research has also begun to account for the dynamic nature of the response of human and natural systems to climate change (Lucier *et al.*, 2006). This research encompasses a wide range of potential impacts on societal needs such as water, health, and agriculture, as well as potential impacts on natural terrestrial and marine ecosystems.

One example of this type of work addresses the potential impacts of variations in water availability in the western United States (Barnett *et al.*, 2004). As mentioned previously, paleoclimatic research indicates that decades-long droughts have occurred many times over the past millennium. This information, in combination with climate model projections of potential reductions in future water availability due to increases in greenhouse gases, suggests that current water management systems in the West (e.g., California) may be insufficient to respond to future climate conditions (VanRheenen *et al.*, 2004; Dettinger *et al.*, 2004). Other research indicates that multi-decadal climate variability in the western United States may have significant impacts on ecosystems, mountain glaciers, tourism, and fire frequency (Christensen *et al.*, 2004; Brown *et al.*, 2004).

Another example of CCSP research related to Goal 4 is analyses of the potential implications of climate variability and change on river and marine ecosystems. For example, measurements of salmon populations originating in Alaskan and Pacific Northwest coastal rivers indicate large fluctuations in abundance in recent decades, resulting in significant economic and social costs and ecological impacts in riverine and coastal marine communities. In addition to impacts from loss of habitat, river obstructions, harvest, and competition from hatcheries there is some evidence that salmon abundance is linked to large-scale climate fluctuations, but details of the processes involved are poorly understood due to the complexity of the food chain upon which the salmon depend (Pierce, 2004; Farley *et al.*, 2006; Ruggerone *et al.*, 2005). Fisheries research has made important strides in understanding the interplay of factors responsible for variations in harvests of many different species, including the effects of water temperature, changing fishing practices, and management of fish hatcheries and migration routes. Another example of multi-factorial coastal research in CCSP is work on coral systems, which has found that human disturbance and coral disease, coupled with ocean warming events, are contributing to coral bleaching (West and Salm, 2003). Research into the potential implications of sea-level rise also points to the need to account for a wide variety of factors when assessing future impacts. For example, some measures to protect coastlines may carry negative side effects, such as the potential for wetlands loss when inland barriers are constructed, preventing the wetlands from migrating inland in response to rising sea level (Cahoon *et al.*, 2006).

Components of CCSP research funded in part through the U.S. Joint Global Ocean Flux Study Program have explored ecosystem impacts in the open ocean resulting from climate variability and change as well as from changes in ocean chemistry and thermal structure. An example of a chemical impact is the chain of events causing the oceans to become more acidic due to chemical changes resulting from the absorption of increasing concentrations of atmospheric CO_2 (Orr *et al.*, 2005). Ocean warming tends to increase vertical stratification (layering) and thus slow the overturning of nutrient-rich deep-ocean waters (Schmittner, 2005). Recent model projections suggest that increased ocean acidification and increased layering of the upper ocean due to warming are likely to reduce plankton production. These model results are supported by satellite observations indicating significant changes in photosynthetic plankton concentrations, including declines in the North Atlantic and Pacific and increases in the Indian Ocean (Gregg *et al.*, 2003).

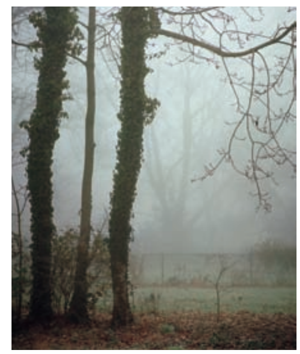
Observational and modeling studies of terrestrial ecosystems indicate a wide variety of changes in which it appears that climate variations play a significant role. For example,

recent evidence indicates a northward expansion of the ranges of many bird and butterfly species in the United States corresponding to warming in the region (Sekercioglu *et al.*, 2004). Declines in Arctic sea ice, observed both *in situ* and by satellites, have been linked to increasing vulnerability of polar bear populations (ACIA, 2005). Satellite and *in situ* observations also indicate a trend toward earlier growth of spring vegetation (Angert *et al.*, 2005). In addition to temperature and hydrologic changes, the increasing level of atmospheric CO_2 is thought to play a role in changing ecosystem distributions and characteristics due to its fertilizing effect. Agricultural yield models account for this effect, and project a range of agricultural impacts depending on the magnitude and nature of future climate change, crop types, and the types of adaptive measures that are adopted. Recent research indicates that different strategies may be required to manage insects, weeds, and diseases in agricultural systems (Ziska and Runion, 2006).

In addition to managed ecosystems, CCSP research has expanded understanding of the sensitivity and adaptability of a variety of other societal sectors. One of these is human health, which may be affected directly by changes in temperature and storm intensity, or indirectly through changes in distributions of insects that carry pathogens. An example of research in this area is the effects of climate change on heat waves. As described in the Climate Variability and Change chapter, recent observational and modeling work suggests that the probability of heat waves such as the one that occurred in Europe in 2003 has increased significantly, and that future warming may make heat waves of similar magnitude a normal summer occurrence within several decades (Meehl and Tebaldi, 2004). Recent research on the societal dimensions of climate variations has shown that physical climate analyses, such as the aforementioned study of heat waves, must be assessed within a complex fabric of other social and environmental factors (Poumadere *et al.*, 2005). An example is the general increase in financial losses due to hurricanes over the past century, which is probably attributable more to expanding coastal development than to any changes in hurricane characteristics (Pielke *et al.*, 2005). In regions such as

central Africa, where the capacity to adapt to environmental variations is often relatively low, recent research has shown strong correlations between year-to-year climate variations and malaria outbreaks (Thomson *et al.*, 2006).

These are a few examples of CCSP's research examining the sensitivity and adaptability of human and natural systems to climate variability and change. It is clear from this work that climate variations can have both beneficial and adverse effects on environmental and socioeconomic systems. However, future projections indicate that the larger the magnitude and rate of climate change, the more likely it is that adverse effects will dominate (NRC, 2002).



Goal 5: Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.

The Nation's basic research on global environmental variability and change has pointed toward a large set of important opportunities for applying the knowledge that is being developed. CCSP is taking three main approaches for exploring and communicating the potential uses and limits of this knowledge, namely the development of scientific syntheses and assessments; adaptive management and planning capabilities; and methods to support climate change policy inquiries.

One key focus of the program's synthesis and assessment activities is its current suite of 21 Synthesis and Assessment (S&A) products, which are intended to provide current evaluations of the science foundation that can be used for informing public debate, policy, and operational decisions, and for defining and setting the future direction and priorities of the program. The Decision Support chapter of this report describes the S&A products more fully, including the first completed product—the report on temperature trends at the surface and in the atmosphere referred to earlier. Another important focus for the program's synthesis and assessment activities is its involvement in the IPCC. The IPCC's major activity is to prepare at regular intervals comprehensive assessments of policy-relevant scientific, technical, and socioeconomic information appropriate to the understanding of human-induced climate change, potential impacts of climate change, and options for mitigation and adaptation. Approximately 120 U.S. scientists are IPCC authors and 15 are Review Editors. The United States co-chairs and hosts IPCC Working Group I, which primarily addresses physical science aspects of climate change. The United States has also played significant roles in the World Meteorological Organization (WMO) / United Nations Environment Programme (UNEP) ozone assessments (WMO, 2003), the Arctic Climate Impact Assessment (ACIA, 2005), and the Millennium Ecosystem Assessment (MEA, 2005), among others.

The second of CCSP's decision-support approaches is the exploration of adaptive management strategies. Activities under this approach develop and evaluate options for adjusting to variability and change in climate and other conditions through "learning by doing" and integrating knowledge with practice. This area of work grows out of the insight that a key to assessment and decision support is close and ongoing interaction between users and producers of information. Many adaptive management projects in the United States are extensions of the first U.S. National Assessment's stakeholder-driven and interdisciplinary collaborations (NAST, 2001).

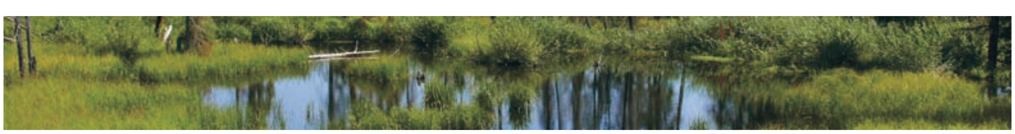
One example of this work is an ongoing project that brings together researchers who study climate processes and their effects on the U.S. Southwest with individuals and organizations that need climate information to make informed decisions (Jacobs *et al.*, 2005). Numerous tangible benefits from this project have helped a wide variety of decisionmakers, from State and local water planners to farmers to public health officials. For example, the project developed a suite of products that make predictions of water availability months in advance, allowing water managers to adjust reservoir levels accordingly to meet the competing demands for this scarce resource.

Another example is the combined use of satellite-based observations of fires and moisture conditions together with seasonal climate forecasts to provide information to fire managers to help them make early and effective decisions about the resources they will need to cope with emerging fires and fire-season dangers. One way in which this information is communicated is through annual workshops targeted separately at eastern and western U.S. fire hazards, which bring together climate scientists and forecasters with fire managers to produce seasonal fire outlooks (see <www.ispe.arizona.edu/climas/conferences/NSAW>). There are many other examples of the exploratory use of seasonal-to-interannual climate information for decisionmaking both domestically and internationally.

In addition to CCSP's work on adaptive management at seasonal-to-interannual time scales, the program is also developing valuable information for long-term (decades to centuries) adaptation issues. One example is the program's analyses of ways in which agricultural practices might be adjusted to take advantage of rising CO_2 levels and to cope with potentially warmer temperatures and decreased moisture availability (Boote *et al.*, 2005). Recent work has shown that sufficient variability exists within some crop species to begin selecting for crop varieties that could maintain or increase yields in a future enhanced-CO_2 environment.

CCSP's third decision-support approach is to help inform inquiries related to climate change policy, in part by using comparative analyses of climate change scenarios. One example is a collaboration between climate scientists and New York City water infrastructure planners that is using regional-scale hydrologic scenarios to inform the long-lasting investments that are being considered in the modernization of the city's water supply system (see <www.ccsr.columbia.edu/cig/taskforce>). Another example is the application of carbon cycle research to assess the potential feasibility, magnitude, and permanence of a variety of different carbon sequestration options (Sarmiento *et al.*, 1999). An initial result from this line of work is the preliminary conclusion that the restoration of inland wetlands could be a particularly efficient means for sequestering carbon in North American prairie lands (Euliss *et al.*, 2006).

Another important way in which CCSP is helping to inform climate change policy inquiries is through integrated assessment modeling, which considers the social and economic factors that may lead to climate change (e.g., greenhouse gas emissions) and the resultant effects of those activities on the Earth system and human welfare. These models are useful for considering the costs and effects of various policy options. One important result of this work suggests that reducing emissions of greenhouse gases other than CO_2 could be an economically efficient first step in reducing the overall atmospheric burden of greenhouse gases (Hansen and Sato, 2004). Another important new set of analyses assesses various policy options while accounting for inherent scientific and economic uncertainty (Webster *et al.*, 2003).



The preceding descriptions provide a thumbnail sketch of the progress CCSP has made toward its goals. However, an important body of work remains within each of these goals that still must be tackled if this Nation is to be fully equipped to wisely address the challenges posed by global environmental variability and change. The *CCSP Strategic Plan* articulates this research agenda, and the research element chapters of this report outline specific examples of work proposed for FY 2007. The research element chapters also include updates on CCSP research-product preparation, milestones, and activities, with reference to the research focus areas for each goal.

CCSP FY 2007 Focus Areas

An important step in coordinating the CCSP budget for FY 2007 has been to align the agency climate programs with the goals and key research focus areas in the *CCSP Strategic Plan*, thus helping to ensure consistency. The emphasis is on ensuring alignment of current funding with a recommended list of priorities and identifying gaps that may occur, as well as identifying measurable milestones and deliverables that reflect accountability toward meeting program goals.

Within the framework provided by the *CCSP Strategic Plan*, there is a continual assessment and refinement of program priorities and activities by means of identified new initiatives and other evolutionary redirections. CCSP aspires to refresh programs during each budget cycle such that over a 5-year period, approximately one-third of CCSP research and observation activities will support new initiatives. Since many research activities involve long-term programs, this refresh rate is representative of the desired balance between program continuity to address complex, long-term issues, and program priorities to respond to new information needs as they arise. Based in part on the analysis of program progress to date and mindful of its priorities in recent years, CCSP has developed a set of near-term focus areas for FY 2007. These focus areas, which constitute only a fraction of the program's overall priorities, are areas in which interagency cooperation is particularly needed and likely to produce significant advances. The focus areas are listed here in the same order as the research elements described in the *CCSP Strategic Plan* and in the order these research elements appear in this document.

Aerosols-Clouds-Climate: Integrating New Remote-Sensing Observations with Expanded In Situ Observations to Advance the Next Generation of Climate Prediction Capabilities. The key objectives of this focus area are to quantify the uncertainty related to aerosol-cloud interactions and to develop for the first time a consensus best estimate of the current magnitude of uncertainty resulting from the effects of aerosols on clouds. This

focus area will capitalize on the first global measurements of aerosol and cloud vertical distributions and properties (i.e., the NASA enhanced "A-train" satellite formation), expanded *in situ* observations (e.g., NOAA's expanded *in situ* observation capabilities), and laboratory and controlled condition characterization of aerosols and their properties, data analysis, and modeling.

Development of an Integrated Earth System Analysis Capability. The purpose of this focus area is to improve the scientific capacity to assimilate current and planned future observations from disparate observing systems into Earth system models that include physical, chemical, and biological processes, in order to produce the best possible synthesized description of the state of the Earth system and how it is evolving over time. This capability will provide a vital information base for diagnosing and improving climate models; understanding the causes and impacts of climate variability and change; improving estimates of sources, sinks, and budgets of important parameters (e.g., water vapor, carbon); and, fundamentally, linking together the Earth system observation and modeling efforts within CCSP.

Integration of Water Cycle Observations, Research, and Modeling: A Prototype Project. The purpose of this focus area is to address significant uncertainties associated with the water cycle through a study that comprehensively addresses the water budget within a limited spatial and temporal domain. The core of this prototype activity is DOE's proposed month-long field campaign at the Atmospheric Radiation Measurement (ARM) site in the southern Great Plains [i.e., the Cloud and LAnd Surface Interactions Campaign (CLASIC)]. The campaign will feature concurrent contributions from NASA, NOAA, NSF, USGS, USDA, EPA, and others to extend CLASIC's time and space domain to capture the seasonal time scale and regional processes, and expand the observational framework by adding space-based observations, aircraft campaigns, surface and subsurface hydrologic components, isotopic measurements, CO_2 fluxes, and associated modeling.

Global Landsat Data for Answering Critical Climate Questions. The purpose of this focus area is to acquire Landsat-like global data for addressing critical climate research questions. Although a scan line malfunction has occurred on Landsat 7, it continues to collect global data. NASA and USGS are investigating alternative sources for Landsat-like data, but have not found a substitute that provides globally available satellite data at spatial scales of tens of meters. These data are required to document land use, land-cover change, glacier extent, and movements of ice sheets, and to address a wide variety of other questions related to climate variability and change. The focus will be on acquiring a global collection of data from other satellites.

North American Carbon Program Integration. The key objective of this focus area is to quantify the carbon budget for the North American region. The research involves integration of remote observations, *in situ* measurements, and models of the atmospheric, terrestrial, and oceanic components of the carbon cycle to quantify carbon budgets at multiple spatial and temporal scales. This information is essential for developing successful carbon management strategies and reducing the uncertainties in quantifying carbon cycle dynamics. These scientific challenges are addressed in this focus area, which involves the North American Carbon Program (NACP), the Ocean Carbon and Climate Change (OCCC) Program, and a *State of the Carbon Cycle Report* that will provide the first integrated analysis of the North American carbon cycle. The research will result in a stronger scientific basis for developing technical and policy options for managing carbon.

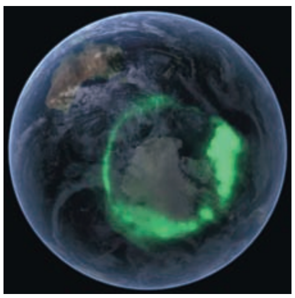
Impacts of Climate Variability and Change on Ecosystem Productivity and Biodiversity. The purpose of this focus area is to increase understanding of the relationship between climate change and ecosystem productivity and biodiversity. A key element is the development of predictive models, at various spatial scales, to provide forecasts for aquatic and terrestrial ecosystems. Emphasis will be placed on ecosystems important to society such as forests, agricultural systems, rangelands, wetlands, fisheries, coral reefs, and alpine, river, estuary, and marine ecosystems. Emphasis will also be placed on regions where abrupt environmental changes may occur, such as high-elevation and high-latitude ecosystems (e.g., western U.S. mountain and arctic systems).

Coping with Drought through Research and Regional Partnerships. The objective of this focus area is to understand how information about near-term climate variability and longer term climate trends can best be used to aid decisionmakers in coping with drought. The approach will include the development of methods, models, and mechanisms for integrating climate information into analyses of the social and economic consequences of drought as well as the policymaking and decisionmaking processes in the face of drought. Climate information utilized in this effort may include paleoclimatic and historical information about climate and its impacts, predictions based on seasonal-to-interannual climate variability, recent trends, and future projections of decadal variability and climate change. Social and economic impact analyses utilized in this effort may include historical perspectives and near-term trends (e.g., projections of water conflicts, water demand, population changes, land-use shifts).

International Polar Year. The International Polar Year (IPY) will be an international suite of coordinated research projects, involving more than 50 nations, planned for 2007 and 2008 in both Arctic and Antarctic polar regions to address the strong links these regions have with the rest of the globe. It will emphasize multidisciplinary research across a wide range of disciplines, including societal and health issues and how these are related to the accelerating changes in the polar environment. Research will focus on a wide range of issues, including trends in extent and thickness of the polar ice sheets and sea ice, polar atmospheric variability, export of continental emissions to the polar regions, changes in the chemical composition of the polar atmosphere, and changing permafrost conditions.

Integrated Ocean Observing System. The international community is developing a strategy for a global ocean observing system in cooperation with the Intergovernmental Oceanographic Commission (IOC), WMO, the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology, and UNEP. A major U.S. contribution to this is the Integrated Ocean Observing System (IOOS), supported by the Administration's U.S. Ocean Action Plan. The *Strategic Plan for the U.S. Integrated Earth Observation System* provides a framework for understanding connections between IOOS and the broader GEOSS. Products from IOOS—such as tsunami warnings, harmful algal bloom forecasts, and real-time navigation services—are already demonstrating their value to the economy, human health, and public safety. Although funding for IOOS is largely outside of the CCSP budget, its strategy is consistent with the requirements for ocean observations in climate research.

One theme shared by many of these focus areas is the improvement of the capacity for Earth system modeling and data integration. Benefits from this integrating theme are expected to include: (a) improvements in climate predictions through advances in model coupling, model components, data assimilation, model parameterizations, and model initialization; (b) improved ability to estimate sources, sinks, and fluxes of key environmental constituents (e.g., carbon, water) required for making many different types of informed decisions such as those regarding carbon sequestration and drought mitigation; (c) improved ability to estimate the effects of climate variability and change on human and natural systems; and (d) improved understanding of Earth system processes, including component interactions, which will provide vital underpinning for future scientific advances. These advances in Earth system modeling and data integration are also critical to the ultimate success of the U.S. Integrated Earth Observation System.



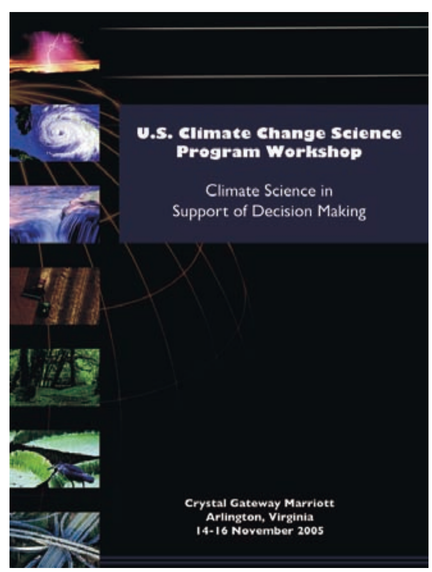
Decision Support: Information to Support Policy Development and Adaptive Management

CCSP sponsors and conducts research that is ultimately related to policy and adaptive management decisionmaking. CCSP's decision-support approach is guided by several general principles, including:

- Early and continuing involvement of stakeholders
- Explicit treatment of uncertainties
- Transparent public review of analysis questions, methods, and draft results
- Evaluation of lessons learned from ongoing and prior decision-support and assessment activities.

CCSP Workshop

CCSP held a workshop, *Climate Science in Support of Decisionmaking*, in November 2005 in which over 700 individuals participated, including an international audience of climate scientists, decisionmakers, and users of information on climate variability and change. A variety of sessions addressed recent and ongoing global change assessments, the application of climate science to adaptive management, and the use of climate information in analyses of policy options. Participants provided positive feedback on this set of opportunities to learn about CCSP's activities and exchange information with scientists, decisionmakers, and other stakeholders. CCSP will use insights from the workshop to guide current and future CCSP decision-support activities, including future forums for dialog on this aspect of the program.



Synthesis and Assessment Products

CCSP is generating synthesis and assessment products to support informed discussion and decisionmaking on climate variability and change by policymakers, resource managers, stakeholders, the media, and the general public. The first of these reports, on temperature trends in the atmosphere and at the Earth's surface, has been completed (see Climate Variability and Change chapter).

The synthesis and assessment products integrate research results focused on key issues and related questions frequently raised by decisionmakers. Current evaluations of the science can be used for informing public debate, policy development, and adaptive management decisions, and for defining and setting the future direction and priorities of the program. The synthesis and assessment products constitute an important new form of topic-driven integration of U.S. global change assessment efforts. These products will be U.S. Government disseminations, subject to the provisions of the Information Quality Act (Section 515 of the Treasury and General Government Appropriations Act of 2001) and the Federal Advisory Committee Act Amendments of 1997 (PUB. L. 105-153, SEC. 2(A), (B), DEC. 17, 1997, 111 STAT. 2689.).

The Decision Support chapter of this report provides a description of each of the products. More information about the products can be obtained from the CCSP web site at <www.climatescience.gov>.

The synthesis and assessment products are being generated by researchers in a process that involves review by experts, public comment from stakeholders and the general public, and final approval by the departments/agencies involved in CCSP. Formal endorsement of the products by the Federal Government will enhance their value for decisionmakers and the public at large. The program has prepared guidelines that describe steps to be followed in each of three phases of the preparation process: developing the prospectus, drafting and revising, and final approval and publication. This methodology for product development facilitates involvement of the research community and user groups in ensuring that the products are focused in a useful fashion and meet the highest standards of scientific excellence. The guidelines also encourage transparency by ensuring that public information about the status of the products will be provided through the Federal Register, on the CCSP web site, and through other means. If further clarification of specific issues is required, the NRC will provide advice on an as-needed basis to the lead agency responsible for the preparation of each product.

SUMMARY OF SYNTHESIS AND ASSESSMENT PRODUCTS

CCSP GOAL 1	Extend knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change.
1.1	Temperature trends in the lower atmosphere: Steps for understanding and reconciling differences.
1.2	Past climate variability and change in the Arctic and at high latitudes.
1.3	Re-analyses of historical climate data for key atmospheric features: Implications for attribution of causes of observed change.
CCSP GOAL 2	Improve quantification of the forces bringing about changes in the Earth's climate and related systems.
2.1	A. Scenarios of greenhouse gas emissions and atmospheric concentrations. B. Global change scenarios: Their development and use.
2.2	North American carbon budget and implications for the global carbon cycle.
2.3	Aerosol properties and their impacts on climate.
2.4	Trends in emissions of ozone-depleting substances, ozone layer recovery, and implications for ultraviolet radiation exposure and climate change.
CCSP GOAL 3	Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future.
3.1	Climate models: An assessment of strengths and limitations for user applications.
3.2	Climate projections based on emissions scenarios for long-lived radiatively active trace gases and future climate impacts of short-lived radiatively active gases and aerosols..
3.3	Weather and climate extremes in a changing climate.
3.4	Abrupt climate change.
CCSP GOAL 4	Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes.
4.1	Coastal elevations and sensitivity to sea-level rise.
4.2	State-of-knowledge of thresholds of change that could lead to discontinuities in some ecosystems and climate-sensitive resources.
4.3	The effects of global change on agriculture, biodiversity, land, and water resources.
4.4	Preliminary review of adaptation options for climate-sensitive ecosystems and resources.
4.5	Effects of climate change on energy production and use in the United States.
4.6	Analyses of the effects of global change on human health and welfare and human systems.
4.7	Impacts of climate variability and change on transportation systems and infrastructure: Gulf coast study.
CCSP GOAL 5	Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.
5.1	Uses and limitations of observations, data, forecasts, and other projections in decision support for selected sectors and regions.
5.2	Best-practice approaches for characterizing, communicating, and incorporating scientific uncertainty in decisionmaking.
5.3	Decision-support experiments and evaluations using seasonal-to-interannual forecasts and observational data.

Commitment to "Lessons Learned" in Decision Support and Assessment

To build on the experiences of earlier assessment activities, CCSP has requested that the NRC carry out an analysis of global change assessments that have addressed topics broadly similar to those encompassed by CCSP. The study will be approached in two steps:

1) The committee will conduct a comparative analysis of past assessments that have stated objectives similar to those of the CCSP. Specifically, the committee will examine the strengths and weaknesses of selected past assessments in the following areas:
   – Establishing clear rationales and appropriate institutional structures
   – Designing and scheduling assessment activities
   – Involving the scientific community and other relevant experts in the preparation and review of assessment products
   – Engaging the potential users of assessment products
   – Accurately and effectively communicating scientific knowledge, uncertainty, and confidence limits
   – Guiding plans for future global change research activities, including observation, monitoring, and modeling of past and future changes
   – Creating assessment products that are valued by their target audiences.
2) The committee will identify approaches (in terms of geographic scale, scope, assessment entity, and timing) and products that are most effective for meeting CCSP's stated objectives for assessments.

Outline of Research Element Activities

The CCSP participating agencies coordinate scientific research through a set of linked interdisciplinary research elements and cross-cutting activities that encompass a wide range of interconnected issues of climate and global change. Chapters 3 to15 of the *CCSP Strategic Plan* contain more detailed discussions of the research elements as well as activities that cut across all areas of the program. This report focuses on highlights of recent research and program plans for FY 2007.

Atmospheric Composition – The composition of the global atmosphere has an influence on climate and the ozone layer, as well as their relation to air quality, all of which have implications for ecosystem vitality and human health. CCSP-supported research focuses on how human activities and natural phenomena affect atmospheric composition, and how those changes relate to societally important issues such as climate change and ozone depletion. Emphasis is on developing the research and observing framework that will provide timely scientific information for decisionmakers in the climate arena, both in the United States and abroad.

See CCSP Strategic Plan Chapter 3.

Climate Variability and Change (including Climate Modeling) – Scientists are increasingly recognizing that short- and long-term climate variability and climate change are intrinsically linked. CCSP-supported research has made significant advances in understanding the causes of climate variations. Substantial progress has also been made in incorporating this new knowledge into frameworks for predicting future climate variability on seasonal-to-interannual time scales and for investigating the effects of human activities on climate. A new generation of climate models incorporates improved representations of physical processes, as well as increased resolution, putting them at the forefront of international research. Despite these improvements, there are still significant uncertainties associated with certain aspects of climate models.

See CCSP Strategic Plan Chapters 4 and 10.

Global Water Cycle – The water cycle plays a critical role in the functioning of the Earth system. Inadequate understanding of the water cycle is one of the dominant causes of uncertainty in climate prediction. The water cycle integrates the complex physical, chemical, and biological processes that sustain ecosystems and influence climate and related global change. New understanding of these processes will be essential to developing options and responses to the consequences of water cycle variability and change.

See CCSP Strategic Plan Chapter 5.

Land-Use and Land-Cover Change – Land use and land cover are linked to climate and weather in complex ways. Key links include the exchange of greenhouse gases between the land surface and the atmosphere, the radiation balance of the land surface, the exchange of sensible heat between the land surface and the atmosphere, and the roughness of the land surface and its uptake of momentum from the atmosphere. Because of these strong links, changes in land use and land cover can be important contributors to climate change and variability.

See CCSP Strategic Plan Chapter 6.

Global Carbon Cycle – CCSP-supported research on the global carbon cycle addresses scientific questions about the size and variability of the dynamic reservoirs and fluxes of carbon within the Earth system; potential short- and long-term changes in carbon cycling; and options for managing carbon sources and sinks to achieve the appropriate balance of risk, cost, and benefit to society.

See CCSP Strategic Plan Chapter 7.

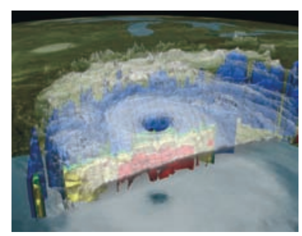
Ecosystems – Global change has the potential to affect the structure and functioning of ecosystems in complex ways. The role of CCSP-supported ecosystems research is to increase the knowledge necessary to evaluate the potential effects of global change on ecosystems in order to help society respond effectively to changes that affect the goods and services provided by ecosystems. Research focuses on changes in ecosystem structure and functioning, potential changes in the frequency and intensity of climate-related disturbances that may have significant consequences for society, and the effects of ecosystems on climate.

See CCSP Strategic Plan Chapter 8.

Decision-Support Resources Development and Related Research on Human Contributions and Responses – Decisionmakers and other interested citizens need reliable science-based information to make informed judgments regarding policy and actions to address the risks and opportunities of variability and change in climate and related systems. A wide variety of CCSP decision-support resources and related research on human contributions and responses is targeted at that objective. The outcomes of these activities are intended to inform public discussion of climate-related issues and scientifically assess and expand options for mitigation of and adaptation to climate variability and change.

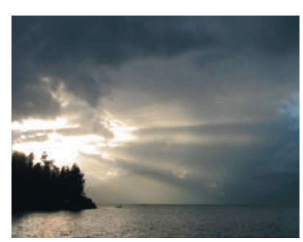
See CCSP Strategic Plan Chapters 9 and 11.

Observing and Monitoring the Climate System (including Data Management and Information) – The Interagency Working Group on Earth Observations has identified near-term opportunities for improved observations in disaster warning, global land cover, sea level, drought, and air quality, and has highlighted enhanced data management as an overarching need. Such cooperative efforts build upon the current GEOSS, including several new Earth-observing satellites, suborbital systems, surface networks, reference sites, and process studies now producing unprecedented high-quality data that have led to major new insights about the Earth's climate system. The United States is contributing to the development and operation of observing systems that will combine the data streams from both research and operational observing platforms to provide for a comprehensive measure of climate system variability and climate change processes.



See CCSP Strategic Plan Chapters 12 and 13.

Communication – CCSP's member agencies support a broad array of communications initiatives. CCSP has developed a strategy and implementation plan for helping to coordinate and facilitate these activities. These efforts are intended to improve public understanding of climate change research by disseminating the results of CCSP activities credibly and effectively, and by making CCSP science findings and products easily available to a diverse set of audiences.



See CCSP Strategic Plan Chapter 14.

International Research and Cooperation – CCSP, through its working groups including the Interagency Working Group on International Research and Cooperation, participates in and provides input to major international scientific and related organizations on behalf of the U.S. Government and scientific community. CCSP also provides support to maintain the central infrastructure of several international research programs and international activities that complement CCSP and U.S. Government goals in climate science.

See CCSP Strategic Plan Chapter 15.

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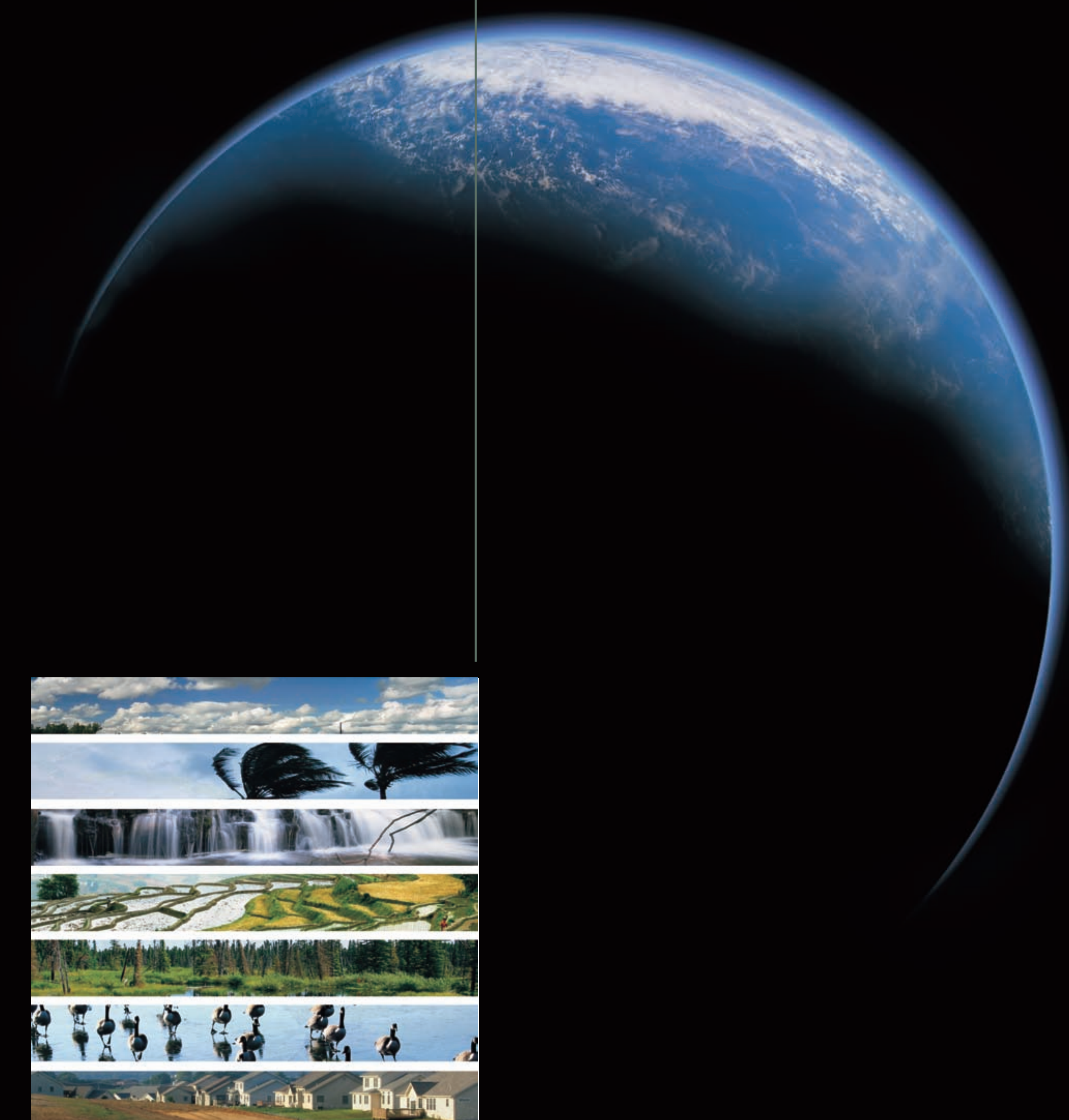
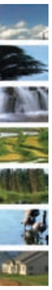
HIGHLIGHTS OF RECENT RESEARCH AND PLANS FOR FY 2007





1 | Atmospheric Composition

Strategic Research Questions

3.1 What are the climate-relevant chemical, microphysical, and optical properties, and spatial and temporal distributions, of human-caused and naturally occurring aerosols?

3.2 What are the atmospheric sources and sinks of the greenhouse gases other than CO_2 and the implications for the Earth's energy balance?

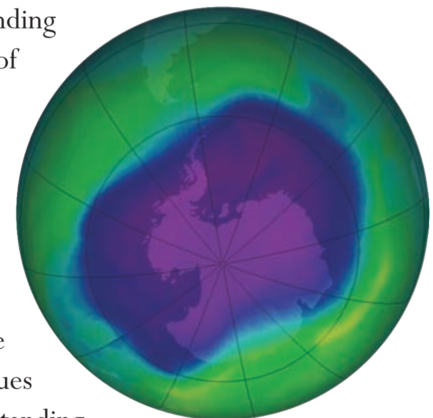
3.3 What are the effects of regional pollution on the global atmosphere and the effects of global climate and chemical change on regional air quality and atmospheric chemical inputs to ecosystems?

3.4 What are the characteristics of the recovery of the stratospheric ozone layer in response to declining abundances of ozone-depleting gases and increasing abundances of greenhouse gases?

3.5 What are the couplings and feedback mechanisms among climate change, air pollution, and ozone layer depletion, and their relationship to the health of humans and ecosystems?

See Chapter 3 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of these research questions.

Earth's atmosphere is a complex mixture of gases and particles. Although most are present at trace amounts of one-millionth or less of the total, those very small abundances are sufficient to play a major role in regional and global issues that affect the well-being of humans and ecosystems. Indeed, changes in atmospheric composition are the drivers of major environment-related issues of today: climate change, depletion of the stratospheric ozone layer, and air quality at the Earth's surface. The composition of the atmosphere is changing due to both natural and anthropogenic influences. The changes have been significant in the approximately 250 years since the beginning of the Industrial Revolution. CCSP is developing a framework for research and observations that will elucidate the processes at work in our atmosphere and the way they influence atmospheric composition and hence climate, the environment, and human health, with the ultimate aim of providing the scientific understanding needed to underpin decisions and planning in the 21st century.



Great strides have been made in the last two decades concerning our understanding of how atmospheric composition relates to the global environment. The cause of the Antarctic ozone hole, first observed in the 1980s and initially a geophysical mystery, has been conclusively linked to the trace amounts of human-made chlorine- and bromine-containing gases released to the atmosphere starting in the 1960s. The rise in greenhouse gases in the atmosphere has been meticulously documented for several decades. The interactions between natural emissions and emissions caused by human activity have been shown to lie at the heart of the quality of the air we breathe. Increasingly, researchers are taking up the challenge of understanding the complex interactions between issues such as climate change, ozone depletion, and air quality. Better scientific understanding holds the promise of enabling future decisions that will be effective across multiple—and interwoven—societal concerns.

CCSP-supported research in atmospheric composition for FY 2007 will have a high-priority focus on improving the predictive understanding of the role of natural and human-influenced aerosols (airborne fine particles) on the climate system. Aerosols interact with radiation directly (by absorbing or scattering radiation) as well as indirectly (e.g., by influencing the formation and properties of clouds). Unlike greenhouse gases, aerosols can either warm or cool the atmosphere through these interactions. Furthermore, the lifetime of aerosols in the atmosphere is shorter than that of many greenhouse gases, therefore the time frame for responding to their influence is correspondingly shorter than for the long-lived greenhouse gases. The understanding of how aerosols influence climate has been identified as one of the most uncertain scientific areas and a high priority for research. The interaction between aerosols, clouds, precipitation, and climate is a specific focus of FY 2007 research in the atmospheric composition component of CCSP. Research also focuses on understanding the role of non-CO_2 greenhouse gases (e.g., changes in water vapor distribution due to human influences) in climate, as well as investigating the long-range processes that transport and transform greenhouse gases in the atmosphere.

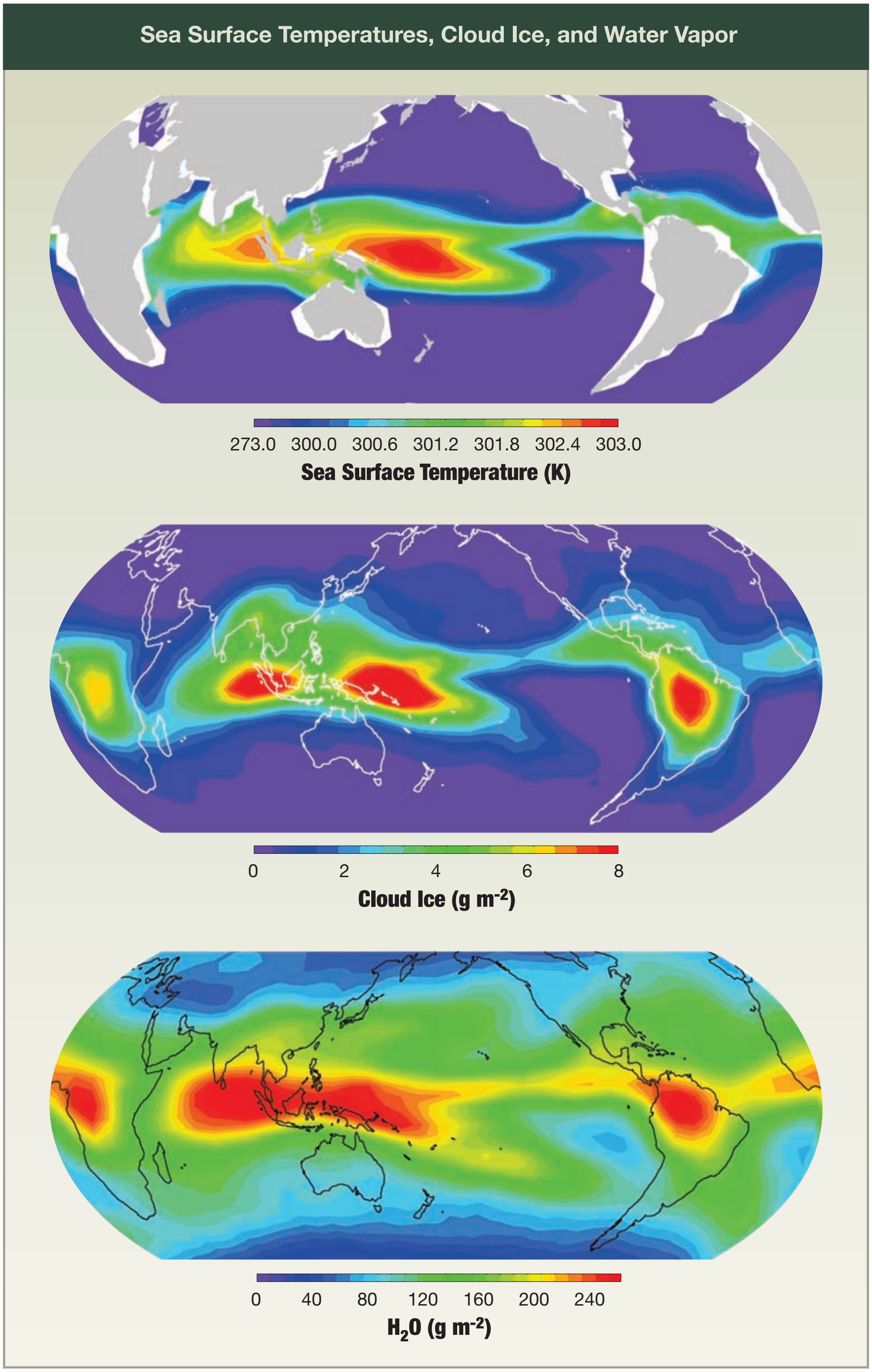
The overall research approach for understanding the role of atmospheric composition is an integrated application of long-term systematic observations, laboratory research, intensive field studies focused on gaining a process-level understanding of atmospheric phenomena, and diagnostic analyses and modeling that advance predictive capabilities. These endeavors are coupled with periodic assessments of understanding and development of products that synthesize findings in ways that are useful to decisionmakers and planners. Research is highly collaborative and involves partnerships throughout the Nation and the world.

Highlights of Recent Research

The following are selected highlights of recent research supported by CCSP-participating agencies.

Upper Atmospheric Water Vapor Trends and Feedbacks.[2,12,13] Climate models predict that as ocean surfaces warm due to a warming climate, the increased evaporation will moisten all levels of the atmosphere, especially the upper atmosphere. Since water vapor is itself a greenhouse gas, this moistening further increases the warming. Models of Earth's climate suggest that this serves as a powerful positive feedback, more than doubling the sensitivity of the surface temperature to anthropogenic greenhouse gas forcing. Regional moistening trends in the lower atmosphere have been observed since the mid-1970s from balloon-borne measurements and are strongly linked to changes in surface temperature. Upper atmospheric trends are, however, difficult to assess from conventional observing systems, such as balloon-borne sensors, due to fundamental limitations of observing capabilities. New CCSP research has used data from the High Resolution Infrared Radiometer Sounder (HIRS) and Microwave Sounding Unit (MSU) satellite instruments to evaluate upper atmospheric water vapor and temperature trends since 1979. The observed trends are consistent with those obtained from global climate model simulations; both indicate moistening over this period. The observed results are starkly different from what would be expected in a "no moistening" scenario, which would have greatly reduced the magnitude of model estimates of future global warming. This study provides strong evidence supporting the capability of current climate models to simulate this important climate process, and adds to the credibility of climate model projections of future global warming.

In other CCSP research, simultaneous observations of water vapor in the upper atmosphere and cloud ice from the Microwave Limb Sounder (MLS) on the NASA Aura satellite have provided new evidence for another kind of positive feedback through convective cloud-induced enhancement of the greenhouse effect in the tropics. The work shows that when sea surface temperature exceeds 27°C (about 300 Kelvin, see Figure 1), water evaporated from the warm surface is carried to the upper atmosphere through the formation of towering cumulus clouds. Ice particles in the upper levels of these clouds eventually evaporate, leaving increased water vapor concentrations in the upper atmosphere. Analyses indicate that this cloud-induced



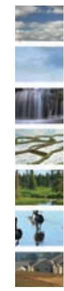


Figure 1: Sea Surface Temperatures, Cloud Ice, and Water Vapor. Observations of sea surface temperature [from the National Center for Environmental Prediction (top)], cloud ice [from Aura Microwave Limb Sounder (MLS, middle)], and upper tropospheric water vapor [from Aura MLS (bottom)] averaged for August 2004 through July 2005. These products illustrate increasing sea surface temperature associated with increasing convective clouds and increasing upper tropospheric water vapor. This convective cloud-induced moistening of the upper troposphere leads to an enhanced greenhouse effect due to water vapor—three times larger than without convection—exacerbating the impact of global warming. *Credit: H. Su, California Institute of Technology/ Jet Propulsion Laboratory.*

moistening of the tropical upper troposphere leads to an enhanced positive water vapor feedback that is about three times larger than what would be expected in the absence of the clouds. Figure 1 illustrate these relationships. These results indicate that convection is an important, if not dominant, process in the previously identified tropical "super greenhouse effect."

A 350-Year Atmospheric History of a Climate-Related Trace Gas.[5] CCSP scientists have published a 350-year atmospheric history of the most abundant sulfur-containing gas in the lower atmosphere, carbonyl sulfide (COS). The research provides the longest atmospheric record of COS to date and shows how the atmospheric abundances of this gas have increased and decreased with industrial sulfur emissions (see Figure 2). Carbonyl sulfide is a relatively long-lived sulfur trace gas with both natural and anthropogenic sources (the latter arising from a variety of industrial processes). Sulfur in COS accounts for about 50% of the sulfate aerosol layer, the atmosphere's layer of sulfate-containing fine particles, during non-volcanic periods. This layer affects depletion of the ozone layer as well as heating and cooling of the atmosphere and hence climate. CCSP researchers analyzed Antarctic air trapped in ice cores and consolidated snow that provided a record of COS concentrations back to about the year 1650. These data suggest that atmospheric amounts of COS increased substantially during the Industrial Revolution, but decreased by about 10% in recent years as global industrial emissions of sulfur declined. Given that a close relationship exists between the atmospheric history of COS and global industrial sulfur emissions,

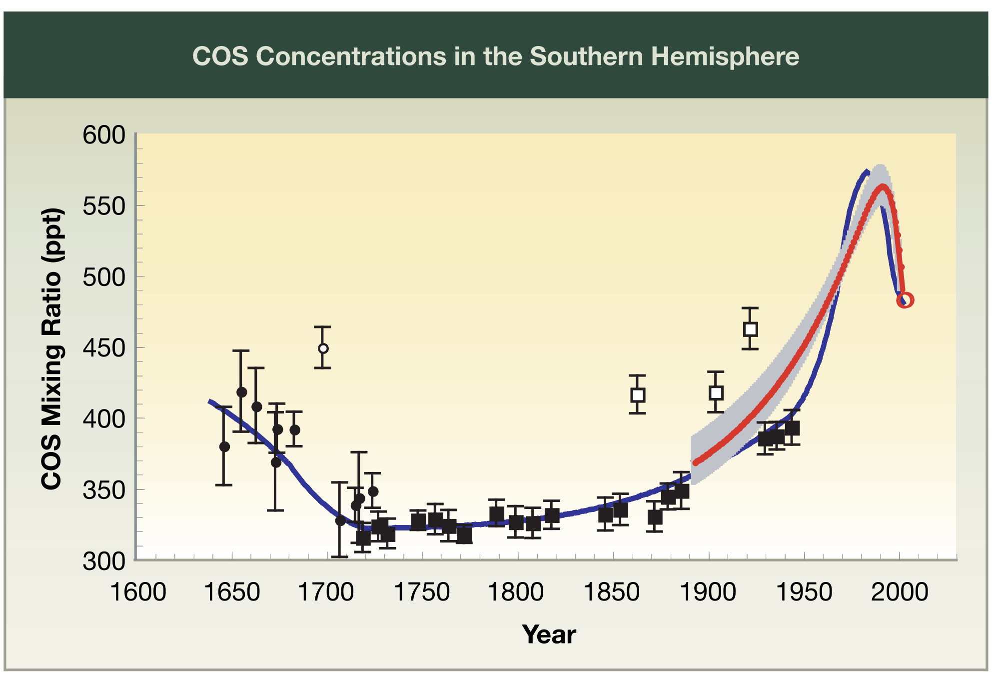
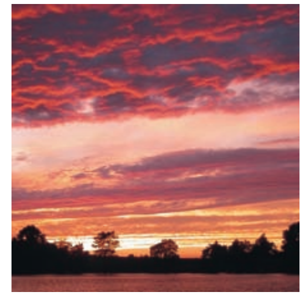


Figure 2: COS Concentrations in the Southern Hemisphere. The blue line represents a history of COS concentrations in the Southern Hemisphere. Note the rather significant increase in concentration coincident with the onset of global industrialization, and the decrease more recently as global sulfur emissions have declined. This history was derived from measurements of COS trapped in ice at Siple Dome, Antarctica (black points) and of COS trapped in the snowpack at the South Pole (red line with grey error bounds). Modern-day measurements from the South Pole and Tasmania are indicated with red circles. Open circle and squares were not used in the calculation because meaningful dates could not be assigned. *Credit: S.A. Montzka, NOAA/ Earth System Research Laboratory.*

the CCSP research suggests that human activities may have contributed to long-term changes in the atmosphere's sulfate aerosol layer.



Assessing and Improving the Inventories of Trace Gas Emissions from North America.[7,8] The CCSP community has made substantial progress in appraising the understanding of North American emissions of trace gases that are precursors for the formation of aerosols and ozone, both of which have implications for climate as well as for air quality in the lower atmosphere. The North American Research Strategy for Tropospheric Ozone (NARSTO) Emission Inventory Assessment, published in FY 2005, is a detailed examination of current approaches to measuring, inventorying, and modeling emissions of trace gases and an assessment of potential improvements to those approaches. Findings of particular note regarding the U.S. National Emission Inventory for mobile sources included: (i) carbon monoxide emissions are about half as large as earlier estimates suggested; and (ii) nitrogen oxide emissions increased throughout the 1990s, contrary to previous assumptions. Accurate estimates of emissions are needed to understand the quantity of aerosols, ozone, and their precursors that are exported from North America to the global atmosphere. Related CCSP research has examined the chemistry of the atmosphere in the New England region, especially with respect to pollutant emissions that affect ozone and aerosols. Findings show a different mix of volatile organic compounds than had been expected; the improved information will lead to a more accurate picture of the chemistry of continental air masses. The New England field research also documented the transport and transformation of aerosols and their associated radiative heating effects as they were carried downwind from their North American sources. This work will enable scientists to reduce the uncertainty in estimates of the effects of aerosols on climate.

Remote Sensing Measurement-based Assessments of Aerosol Direct Radiative Forcing.[14] Greenhouse gases and aerosol particles influence the climate system. While increasing greenhouse gases warm the climate system, aerosol particles have a diverse set of both cooling and warming influences on climate. Current scientific assessment finds that the net effect of aerosols is mostly to cool the climate system, temporarily reducing the impact of greenhouse gases on warming. Even though the greenhouse-gas warming is larger than the aerosol cooling, the uncertainty in the aerosol effect is five times larger than the uncertainty in the greenhouse effect. Reducing these uncertainties is critical to understanding of the climate system and its future change.

Aerosols have both direct and indirect cooling effects on climate. The direct cooling effect is due to the aerosol particles' reflection of sunlight to space. Indirect effects include aerosol-induced changes in cloud properties, cloud distribution, and precipitation that can cool the Earth by enhancing cloud reflectivity. Past assessments of the direct

effect of aerosols on climate were conducted through modeling efforts. Now, CCSP research has assessed the direct impact of aerosols on climate through global measurements. New satellite sensors introduced in the last decade, as well as the Aerosol Robotic Network (AERONET), a global network of ground-based remote-sensing instruments, have provided the opportunity to make a measurement-based assessment of the aerosol direct effect on climate. A major scientific synthesis and assessment of the aerosol direct effect on climate has been completed, published, and served as a major resource for Working Group I of the Intergovernmental Panel on Climate Change (IPCC) in the preparation of its Fourth Assessment Report. The paper reviews recent progress in characterizing aerosols and assessing the aerosol direct effect, focusing on measurements. High-accuracy satellite measurements of aerosol properties have made it feasible to obtain observational constraints for the aerosol direct forcing, especially over the global ocean. Measurements show that aerosols in total reflect about 10% of incoming sunlight to space, much more than the models had indicated. The human contribution to the global aerosol concentrations suggested by the models agrees with the measurement assessment to within measurement accuracy and is on order of approximately 20%.

This review also identifies several issues that require significant future research efforts. Estimates of aerosol forcing over land are less well constrained than over ocean. Uncertainties in estimates of aerosol forcing are also larger on regional scales than on a global scale. The aerosol forcing under cloudy conditions remains relatively unexplored and quite uncertain. In addition, knowledge of the much more complex and probably more important aerosol indirect effects that modify cloud properties and abundance is much less certain and near-term interagency plans reflect the high priority placed on improved characterization of these aerosol-cloud interactions.

Improved Estimates of Organic Aerosols in the Lower Atmosphere.[4] Atmospheric aerosols are involved in issues ranging from air quality to climate change. Recent airborne measurements indicate that computer model simulations of aerosol composition severely underestimate the actual concentrations of organic aerosols in the free troposphere. The Asia-Pacific Regional Aerosol Characterization Experiment (ACE-Asia) was conducted in April and May of 2001. This large field campaign included two aircraft focused on sampling Asian aerosols transported over the Northwest Pacific Ocean. Three different teams of scientists made measurements of organic aerosols in the troposphere, from the surface to around 6.5 km. Results from the groups were very similar and showed that above 2 km, the concentrations of organic carbon were 10 to 100 times higher than the computer models predicted. However, the models were able to replicate adequately the concentrations of sulfate and elemental carbon, other aerosols that were also measured from the aircraft. The scientists believe that the underestimation of organic carbon by the models is due to secondary organic aerosols, which are formed in the troposphere from the oxidation of volatile organic compounds. They are long-lived and can therefore play a large role in intercontinental pollution transport and radiative forcing of climate.

Relative Humidity and the Influence of Atmospheric Particles on Climate.[1,9,10] CCSP researchers have conducted several studies of how atmospheric humidity affects aerosols and the implications for the climate system. The warming and cooling effects of aerosol particles are among the most uncertain of the influences on climate. Many factors affect how aerosol particles interact directly with light, including the relative humidity of the atmosphere, which can affect the size of the particles. CCSP researchers have conducted several studies that show that the chemical composition of the aerosol is the overriding factor in how size changes with relative humidity. Aerosols that are largely inorganic in composition, such as those containing sulfate or sea salt, tend to take up water and grow larger in more humid atmospheres. Consequently, they scatter more light and hence have a larger climate cooling influence (shown schematically in Figure 3). On the other hand, aerosols that are primarily organic are more hydrophobic, and their interaction with light does not change much as the relative humidity of the atmosphere varies. CCSP research spanned a full range of approaches, including fundamental laboratory studies, analysis of extensive field measurements of aerosols in regions of Asia and North America, and modeling investigations. The work has clearly demonstrated that not all aerosols are alike when it comes to their effects on climate. Because aerosol composition was shown to be such a major factor, one implication is that the climate effects of aerosols will change as the aerosol ages and its chemical composition changes. Climate effects therefore

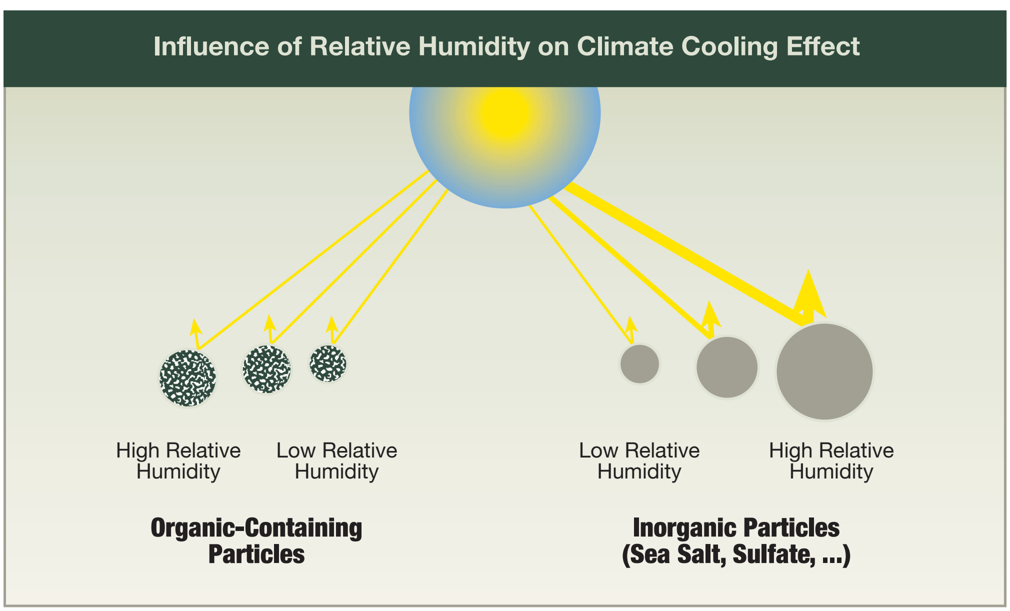


Figure 3: Influence of Relative Humidity on Climate Cooling Effect. Schematic contrasting how relative humidity influences the climate cooling effect of inorganic versus organic aerosol particles. *Credit: A.R. Ravishankara, NOAA/Earth System Research Laboratory.*

evolve as aerosol particles are transported from their original source. The research has led to more accurate representations of aerosol interactions in climate radiative calculations and will thereby improve the accuracy of estimates of the direct climate forcing by aerosols.

Cloud- and Aerosol-Related Fundamentals Elucidated.[6] The interactions between water vapor and condensed forms of water in the atmosphere underlie many of the physical processes that govern cloud formation. Cirrus clouds, polar stratospheric clouds, and the large volume of the atmosphere that has a temperature below freezing are key climate-relevant phenomena that depend on the fundamental physical properties of water vapor, liquid water, and ice. Furthermore, the formation of aerosols and the chemical processes within them are affected by heretofore poorly understood processes specific to water that is supercooled below the freezing point. CCSP research has resulted in a comprehensive review of the fundamental physical processes at the vapor/water/ice interface and an advancement of the parameterization of those processes that are most relevant to atmospheric composition and climate. The work provides a first look at the full range of temperature conditions relevant to the atmosphere, yielding new perspectives on processes pertinent to colder regions, such as the Antarctic stratosphere, that had not been previously considered. Various structural forms of liquid water and solid ice are shown to behave differently, thus research has highlighted the need to represent these aspects of real-world behavior in models of atmospheric chemistry and climate. In addition, the work has implications for methodologies used to calculate relative humidity in laboratory applications and in the real atmosphere.

Smoke Suppression of Clouds: A Climate-Related Effect of Aerosol Particles.[3] Improved modeling capabilities have enabled CCSP researchers to simulate smoke-cloud-surface interactions in biomass-burning regions and to study the mechanisms by which smoke suppresses cloud formation.

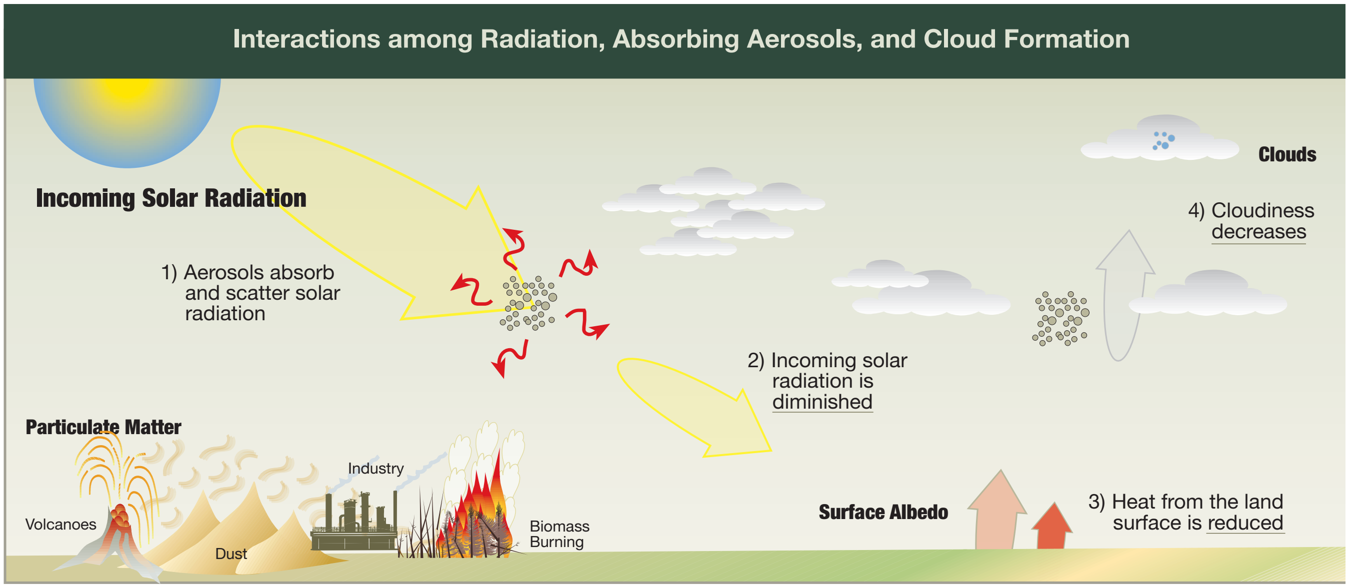


Figure 4: Interactions among Radiation, Absorbing Aerosols, and Cloud Formation. Schematic showing the interactions among radiation, absorbing aerosol particles in smoke, and cloud formation. *Credit: G. Feingold, NOAA/Earth System Research Laboratory.*

The model includes unprecedented treatment of coupled smoke aerosol-cloud-radiative feedbacks in three-dimensional simulations of biomass-burning regions of Amazonia. Absorbing aerosol particles, such as smoke particles, can affect cloudiness by modifying heating rates and atmospheric stability, by modifying how much cloud droplets are heated, or by modifying heat flows from the land surface. CCSP research has evaluated the relative importance of these processes in continental areas, demonstrating that the primary reason for smoke suppression of clouds is the reduction of surface heat flow caused by the presence of absorbing smoke particles (shown schematically in Figure 4). Further, the change in surface heat flow may cause changes in climate-relevant cloud properties, such as cloud amounts. However, the ultimate effect on cloudiness is case-specific and is highly dependent upon cloud type, smoke quantity and properties, location of the smoke within the atmosphere and relative to the clouds, and the degree to which surface heat flows are reduced. The research has helped to quantify a poorly understood aspect of the influence of atmospheric aerosol particles on the climate-related phenomena of cloudiness and surface heating.

Ozone Layer Shows Signs of Recovery.[11] New CCSP research has found that the atmosphere's protective ozone layer is no longer decreasing over much of the globe. The work is based on several different satellite records and surface monitoring instruments. Previous studies have shown that ozone in the topmost layer of the atmosphere may have stopped declining. However, very little ozone is in these top layers. The latest work focuses on the thickness of the entire ozone column above the Earth's surface, and therefore has relevance to the amount of harmful ultraviolet radiation reaching the surface of the Earth. Using satellite-derived estimates of ozone levels, as well as ground-station data from North America, Europe, Hawaii, Australia, and New Zealand, researchers found that total column ozone amounts over the southern mid-latitudes have stopped declining and leveled off, while amounts over the mid- and high latitudes of the Northern Hemisphere have increased since 1996. While the study indicates the beginning stages of improvement in the ozone layer, ozone amounts are still lower than those observed 25 years ago and full recovery lies decades in the future.

Highlights of Plans for FY 2007

CCSP will continue to gather and analyze information through measurement, modeling, and assessment studies to enhance understanding of atmospheric composition and of the processes affecting atmospheric chemistry. Key research plans for FY 2007 follow.

Climate and Ozone Layer Assessments. CCSP research and leadership are playing a substantial role in international efforts to assess the state of scientific understanding with regard to climate and the ozone layer. Major preparation stages of the IPCC's Fourth Assessment Report are occurring during 2006, with many CCSP scientists serving as authors and reviewers; the United States provides the co-chair of IPCC's Working Group I and hosts its Technical Support Unit. In addition, the international assessment of ozone layer depletion was drafted and is being reviewed during 2006. Publication of both the climate and ozone layer assessments will occur in FY 2007.

These activities will address Questions 3.1, 3.2, 3.4, and 3.5 of the CCSP Strategic Plan.

Climate Field Study in the Texas/Gulf of Mexico Region. In August and September of 2006, CCSP researchers in several agencies, institutions, and academia led and participated in a field program that investigated important scientific questions that are common to both climate and air quality. The Gulf of Mexico Atmospheric Composition and Climate Study (GoMACCS) component will focus on providing a better understanding of the sources and atmospheric processes responsible for the formation and distribution of ozone and aerosols in the atmosphere and the influence that these species have on regional and global climate. Analyses will continue in FY 2007.

These activities will address Questions 3.1 and 3.3 of the CCSP Strategic Plan.

Evaluating the North American Contributions to "Greenhouse" Ozone. CCSP research will analyze ozone profiles measured across mid-latitude North America during a 2004 climate field study, with the aim of estimating how much ozone forms over the continent in the summer. Further studies will elucidate the export of ozone from North America to the North Atlantic Ocean and Europe. Ozone in the lower atmosphere is a greenhouse gas that affects climate because it absorbs infrared radiation.

These activities will address Question 3.3 of the CCSP Strategic Plan.

Analysis of Ozone and Ozone-Depleting Substances Data Sets for Trends and Ozone-Layer Recovery Detection. Decisions over the last 2 decades with regard to the protection of the stratospheric ozone layer have resulted in declining use of ozone-depleting substances (ODS). An important focus now is documenting and understanding how the atmosphere is responding to those decisions, both with regard to ODS abundances (which in general are in decline) and the ozone layer itself. Satellite and ground-based data sets have established a multi-decadal record that will be increasingly scrutinized for signs of recovery of the ozone layer via analyses of ozone and ODS.

These activities will address Question 3.4 of the CCSP Strategic Plan.

Oklahoma City Field Study. A field campaign to study North American aerosols involving CCSP scientists from multiple agencies is planned for the summer of 2007. Anthropogenic aerosols are relatively short-lived in the atmosphere and therefore have a high degree of variability over space and time. For this reason, a large contrast in aerosol properties is expected to be found between the upwind and downwind regions of their urban source area. The campaign will investigate the role of such differences for a mid-size, mid-latitude metropolitan area in North America and the consequences for the warming and cooling effects of aerosols. In addition, the campaign will evaluate changes to aerosols as they move through relatively simple fair-weather cumulus systems found over much of mid-latitude North America during the summer months.

This activity will address Question 3.1 of the CCSP Strategic Plan.

Megacity Initiative: Local And Global Research Observations (MILAGRO). The goal of the MILAGRO project is to characterize emissions, chemical transformations, and aerosol and pollutant outflow from Mexico City, the world's second largest megacity. In 2007, CCSP scientists supported by NSF, DOE, and NASA will analyze and evaluate data collected during the 2006 campaign. Field measurements involved numerous ground sites and research aircraft, which along with satellite observations provide information at multiple spatial scales, ranging from the urban Mexico City "super site" to larger areas extending downwind into the Gulf of Mexico. U.S. scientists together with university and government scientists from Mexico will review MILAGRO data and analysis plans at a workshop in Boulder, Colorado, in FY 2007. The data will enable characterization of the evolution of the Mexico City plume, including changes in reactive trace gas concentrations; the evolution of chemical, physical, optical, and cloud nucleating properties of aerosols; and the interactions between gases and aerosols. These measurements and analyses should prove valuable for developing and testing models of aerosol evolution.

These activities will address Question 3.3 of the CCSP Strategic Plan.

Improve Estimates of Aerosol Direct Radiative Forcing via Satellite Data Analysis. Much progress has been made in using global observations from space to assess aerosol radiative forcing. The lidar instrument aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, launched 28 April 2006, promises to revolutionize knowledge of aerosol vertical distribution and greatly expand knowledge of the effects of aerosols in the lowermost atmosphere. Efforts are being made to develop methods of integrating global satellite observations with *in situ* and surface data to fill in major gaps in observations of aerosol particle properties (e.g., how they scatter versus absorb light), and to help separate anthropogenic from natural components. Further advances in the near term are also expected from multi-angle, ultraviolet, and polarization-based techniques for measuring the amount of aerosols in the atmosphere over land surfaces.

These activities will address Question 3.1 of the CCSP Strategic Plan.

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2 | Climate Variability and Change

Strategic Research Questions

4.1 To what extent can uncertainties in model projections due to climate system feedbacks be reduced?

4.2 How can predictions of climate variability and projections of climate change be improved, and what are the limits of their predictability?

4.3 What is the likelihood of abrupt changes in the climate system such as the collapse of the ocean thermohaline circulation, inception of a decades-long mega-drought, or rapid melting of the major ice sheets?

4.4 How are extreme events, such as droughts, floods, wildfires, heat waves, and hurricanes, related to climate variability and change?

4.5 How can information on climate variability and change be most efficiently developed, integrated with non-climatic knowledge, and communicated in order to best serve societal needs?

See Chapter 4 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of these research questions.

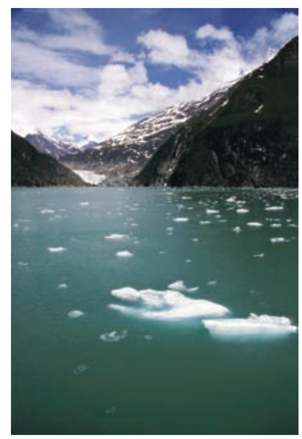
Climate variability and change occur across a broad range of time scales, from short-term variations that contribute to droughts, floods, and changes in hurricane activity, to longer term variations and changes that occur at decadal, centennial, and millennial time scales. CCSP-supported research has focused on advancing understanding of the causes of climate variations across this broad spectrum of time scales, and developing new capabilities to predict future climate variability and project longer term changes due to both natural and anthropogenic forcing. Increasingly, advances from CCSP-sponsored research are being used to develop new climate products and provide science-based information required by decisionmakers, policymakers, and stakeholders to deal with critical issues at local to national levels.

As defined in the *CCSP Strategic Plan*, the Climate Variability and Change (CVC) research component focuses on two broad, critically important questions:

- How are climate variables that are important to human and natural systems affected by changes in the Earth system resulting from natural processes and human activities?
- How can emerging scientific findings on climate variability and change be further developed and communicated in order to better serve societal needs?

More specifically, CVC research addresses the five strategic research questions listed on the facing page in order to achieve the milestones, products, and payoffs described in the *CCSP Strategic Plan*. Cooperative efforts involving several CCSP agencies have led to significant progress in addressing all five of these strategic questions. The highlights below provide a cross-section of some of the major scientific advances achieved during this past fiscal year and illustrative examples of plans for FY 2007.

HIGHLIGHTS OF RECENT RESEARCH



The highlights of recent research on climate variability and change presented here are generally arranged by time scale, extending from paleoclimate through more recent climate characterizations. Additional subsections illustrate important progress in understanding fundamental climate processes and in identifying projected changes. The topics "Climate Model Evaluation, Diagnosis, and Improvement" and "Detection and Attribution of Climate Change" are given special attention in this section.

Paleoclimate

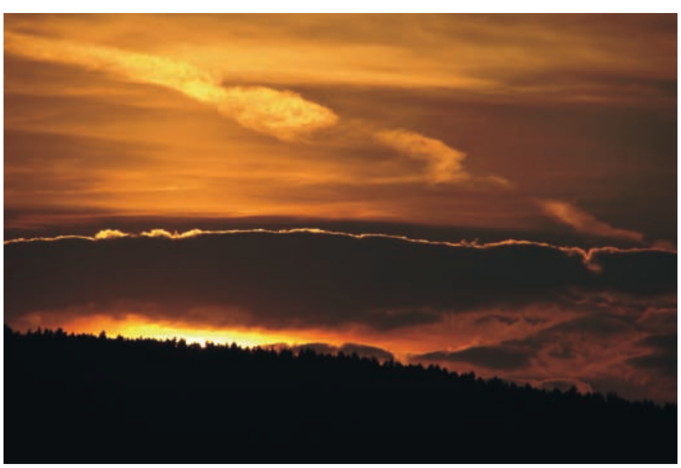
This section begins with an example of the use of paleoclimatic (i.e., prehistoric climate) data to improve understanding of natural climate variability.

High-Resolution Records of Prehistoric Climate.[4,10,30,37,42,44,56] Researchers have developed new high-resolution data records detailing paleoclimatic variations in ancient terrestrial and marine environments. Many of the records span the last ten to twenty thousand years, and some extend back several million years. These records, which are based on a variety of climate proxies (e.g., tree rings, pollen, fossil shells, foraminifera, diatoms), are being used to document multi-decadal and longer term trends in temperature and precipitation. This information is also being used to evaluate climate system variability, such as the influences of solar variability, changes in the position of the Intertropical Convergence Zone (ITCZ), and effects of large-scale climate patterns and processes (e.g., the North Atlantic Oscillation and El Niño) on regional climate. New data from rapidly accumulating sediments have also provided evidence of abrupt climate changes in the past related to changes in deep ocean circulation and other processes. Many of the records are the results of published scientific research contributed to the World Data Center for Paleoclimatology, operated by the National Climatic Data Center (<www.ncdc.noaa.gov>). For proxy information relevant to surface temperature reconstructions over the last 1,200 years or so, considerable effort has gone into testing the sensitivity of the reconstructions to the methods used. Recent results are in general agreement with previously published hemispheric-scale reconstructions and suggest that further improvements will depend more on the quality, rather than the quantity, of available proxy data. This conclusion and, more generally, the state of the science in reconstructing surface temperature records over the past one to two millennia, was the topic of a recent report by a panel of the National Research Council (NRC).

Recent Observed Changes

The following research highlights illustrate some recently observed climate system changes.

CCSP Synthesis and Assessment Report on Atmospheric Temperature Trends.[6,31,45,48] Taking advantage of new surface, satellite, and radiosonde data and new model simulations of 20th century climate, CCSP Synthesis and Assessment Product 1.1 addresses temperature changes from the surface through the lower stratosphere, differences in these changes at various levels, and our understanding of the causes of these changes and differences. It assesses progress made since production of reports by the NRC and the Intergovernmental Panel on Climate Change (IPCC) in 2000 and 2001, and highlights several fundamental uncertainties and differences between and within the individual components of the existing observational and modeling systems. It is particularly relevant to the CCSP Goal 1 focus on increasing confidence in the understanding of how and why climate has changed. The study focuses on the period since 1958, when upper-air soundings by balloon-borne instruments started to become widespread, and on the period since 1979, when the satellite era of atmospheric temperature sounding began. Conclusions include the following:



- *Surface Temperatures* – For global-mean changes, as well as in the tropics (20°S to 20°N), all data sets

show warming at the surface since 1958, with a greater rate of increase since 1979. The global average surface warming from 1958 to the present was 0.12°C per decade and the warming from 1979 to the present was 0.16°C per decade. Differences between various surface data sets are small.

- *Tropospheric Temperatures* – Global-mean temperature in the troposphere (the lower 10 km of the atmosphere) increased at about 0.14°C per decade since 1958, and between 0.10°C and 0.20°C per decade since 1979. In the tropics, temperature increased at about 0.13°C per decade since 1958, and between 0.02°C and 0.19°C per decade since 1979. All data sets show that the global-mean and tropical troposphere has warmed from 1958 to the present, with the warming in the troposphere being slightly more than at the surface. However, due to considerable disagreements between tropospheric data sets since 1979, it is not clear whether the troposphere has warmed more or less than the surface in the past two and half decades. Evidence suggests that non-climatic influences remaining in some or all of the observed tropical tropospheric data sets lead to biased long-term trends and are responsible for the large range in the observed values.
- *Lower Stratospheric Temperatures*: All data sets show that the stratosphere has cooled considerably from both 1958 and 1979 to the present, although there are large differences in the linear trend values from different data sets. Stratospheric cooling is expected from an increase in greenhouse gases. The largest differences between data sets are in the stratosphere, particularly between the radiosonde and satellite-based data sets. It is very likely that the satellite-radiosonde discrepancy arises primarily from uncorrected errors in the radiosonde data.

When state-of-the-art climate models are run with natural and human-induced forcings, simulated global-mean temperature trends for individual atmospheric layers are consistent with observations. Comparing trend differences between the surface and the troposphere exposes discrepancies between model simulations and observed data in the tropics. In the tropics, the majority of observational data sets show more warming at the surface than in the troposphere, while almost all model simulations have larger warming aloft than at the surface.

Several research efforts were catalyzed in part by the production of this synthesis and assessment product during the research community's input to its early stages. One of these studies concluded that an error in the satellite data associated with the day-night temperature cycle reduces the observed warming aloft. Another study concluded that changes in instrumentation of balloon-borne sensors have introduced a spurious cooling anomaly in upper air temperatures measured by those sensors. When these observational factors are accounted for, the observations and models come into closer agreement.

Melting Sea Ice.[9,38,53,59] On September 21, 2005, NASA and the National Snow and Ice Data Center observed the lowest extent of Arctic sea ice (5.3 million km^2) in the satellite record, which extends back to 1978 (see Figure 5). This brings the estimated decline in perennial Arctic sea ice to 9.8% per decade over the satellite record. The period 2002-2005 showed ice extents that were approximately 20% below the 1978-2000 average—a reduction in area of 1.3 million km^2 (or twice the size of Texas). The persistence of near-record low sea-ice extent raises concern that Arctic sea ice may be in a continual, long-term decline. Models driven by projected increases in greenhouse gases project a decrease in summer sea ice of more than 50% over the 21st century, although such projections should be tempered by the recognition that simulations of present-day sea ice generally differ from observed seasonal and geographical distributions. According to paleoclimatic records, there is no evidence of an ice-free summer Arctic during the last 800 millennia.

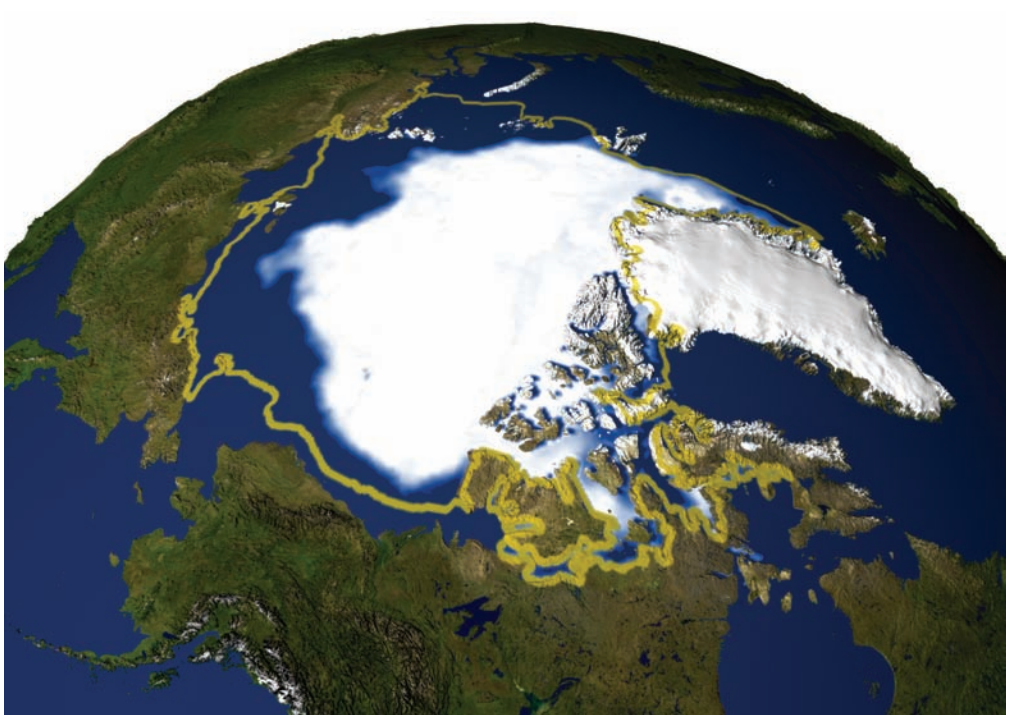


Figure 5: Arctic Minimum Sea-Ice Extent. MODIS color composite image of the Arctic showing the minimum sea-ice extent in 2005 (white) and the average of the 1979–2004 annual minima (yellow line). *Credit: G. Shirah, NASA/ Goddard Space Flight Center.*

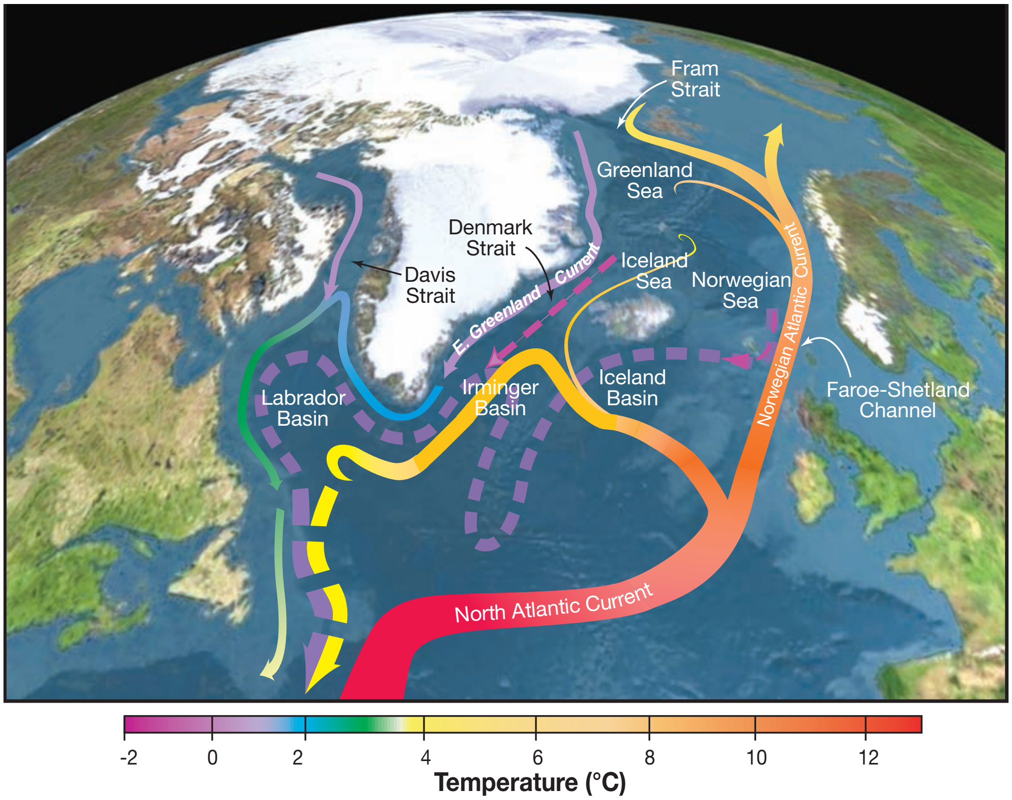
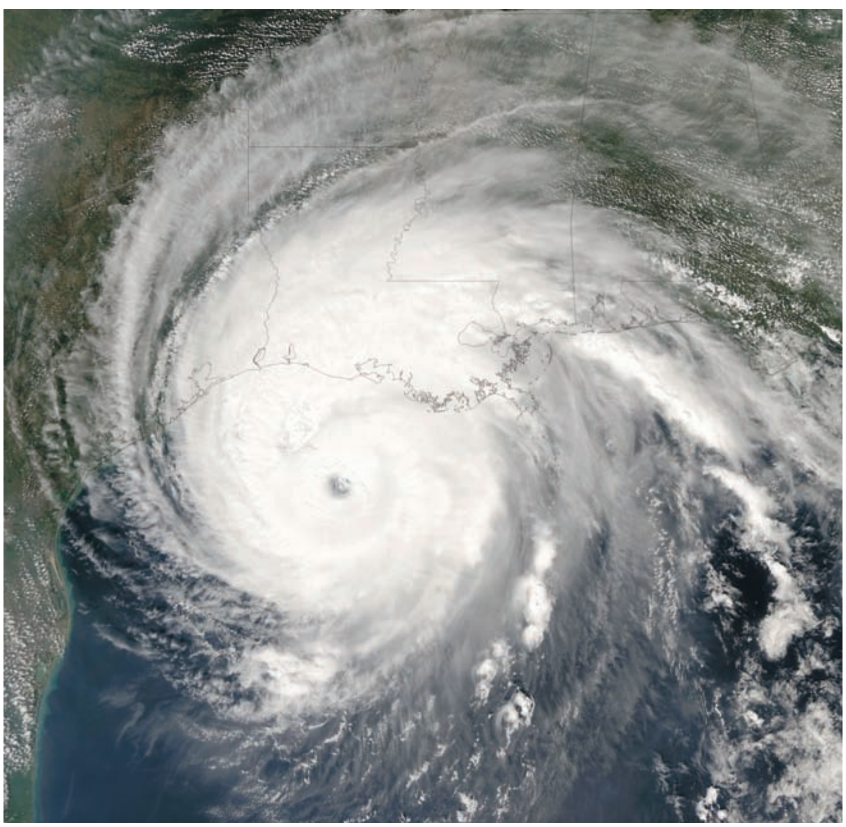


Figure 6: The Atlantic Meridional Overturning Circulation. Topographic map of the Nordic Seas and subpolar basins with schematic circulation of surface currents (solid curves) and deep currents (dashed curves) that form a portion of the Atlantic meridional overturning circulation. Colors of curves indicate approximate temperatures. *Credit: R. Curry, Woods Hole Oceanographic Institution (reproduced with permission from* ***Science****).*

Declining North Atlantic Salinity.[11] An analysis of oceanographic salinity data indicates that large amounts of freshwater have been added to the northern North Atlantic Ocean since the mid-1960s. This work quantified for the first time the volume and time evolution of this freshwater intrusion as well as its extension into the Nordic Seas and subpolar basins. The pattern of freshwater accumulation observed in the Nordic Seas suggests it would take nearly a century to reach freshening thresholds that could abruptly shut down the primary processes governing the meridional overturning (thermohaline) circulation in the North Atlantic. This circulation pattern, which consists of a northward surface component and a southward deep ocean component, is particularly important because it helps maintain relatively moderate temperatures in western Europe, among other things (see schematic diagram in Figure 6).

Fewer Days of Ice on Northern New England Rivers.[20] The total number of days of ice on northern New England rivers has declined significantly in recent decades, particularly in the spring. In a recent study, hydrologists examined data from streamflow gauging stations in Maine, New Hampshire, and Vermont that measure the height and flow of rivers. They examined the number of days each year of ice-affected flow—that is, days when there is enough ice in a river to affect the relation between the height and the flow of the river. They found that the number of ice-affected flow days decreased significantly during the 20th century for 12 of the 16 rivers studied. The total days of ice-affected flow decreased by an average of 20 from 1936 to 2000, with most of the decrease occurring since the 1960s. On average, ice-out dates were 11 days earlier in 2000 compared to 1936, again with most of the change occurring since the 1960s. The changes are consistent with warming temperatures in the late winter and spring in New England during the last 30 to 40 years. Another study of lakes in the region showed that ice-out dates were approximately 5 days earlier in 2000 compared to 1968 in northern and mountainous areas of Maine and New Hampshire and approximately 13 days earlier in more southerly areas of these states.

Hurricane Intensity Trends.[13,14,23,40,41,54] A pair of studies suggests a global average increase in the overall intensity, but not frequency, of hurricanes over approximately the last three decades. One study found a trend toward increasing potential destructiveness of tropical storms, as measured by "total power dissipation" measured over the lifetime of the storms. Changes in potential destructiveness were highly correlated with long-term trends in tropical sea surface temperatures (SSTs) over this period. A second study found a large increase in the number and proportion of hurricanes reaching very intense status, as defined by Saffir-Simpson categories 4 and 5, with the greatest increases occurring in the North Pacific, Indian, and southwest Pacific Oceans. As in the first study, the intensity increases are correlated with long-term increases in tropical SSTs observed in the global oceans. Interestingly, the overall numbers of tropical cyclone days have decreased in all of the global ocean basins except the North Atlantic over the past few decades. While these studies are consistent, the results do not definitively link the trends in tropical cyclone intensity to global warming, and some experts caution that deficiencies in past observations of hurricanes preclude confident identification of trends over this period. Other work has emphasized the vital importance of changing demographics and land use in coastal regions in increasing societal vulnerability to these storms, independent of any changes in hurricane intensity or frequency.



Observed Response of Temperature and Precipitation to Increase in Vegetation Greenness

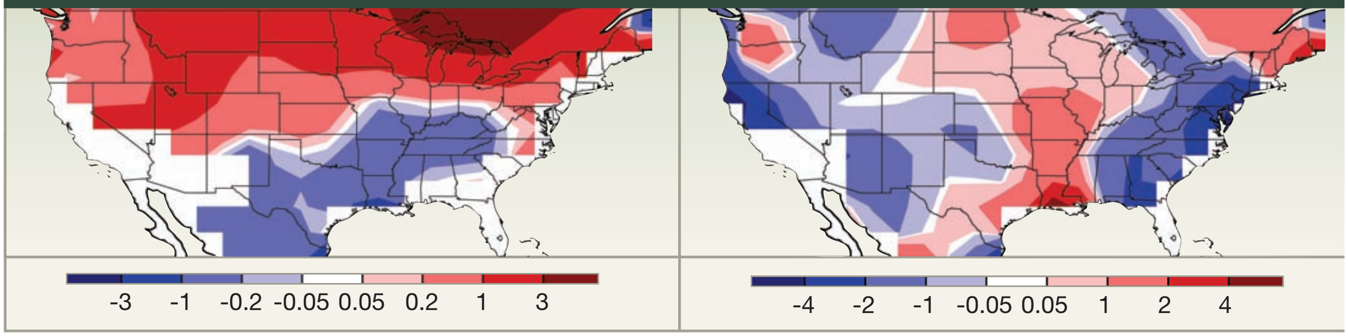
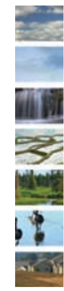


Figure 7: Observed Response of Temperature and Precipitation to Increase in Vegetation Greenness. (Left) Observed response of temperature to an increase in vegetation greenness, calculated from satellite observations. The units are °C per 0.1 FPAR (fraction of photosynthetically available radiation absorbed by the plant canopy). This illustrates vegetation feedbacks on temperature resulting from month-to-month variability in leaf and plant amount. (Right) Same as the left figure, but showing the response of precipitation to a change in vegetation. Units are cm/month per 0.1 FPAR. *Credit: Z. Liu, University of Wisconsin (reproduced from the* ***Journal of Climate*** *with permission from the American Meteorological Society).*



Fundamental Understanding of Climate Processes

Much of the work within the CVC research element focuses on improving fundamental understanding of climate processes. The following research highlights are examples of this type of work.

Vegetation-Climate Feedback.[28,35] While it is well known that climate is an important driver of vegetation growth, less is known about the potential influence of vegetation on climate. To date, two-way vegetation-climate interactions (i.e., feedbacks) have been mostly studied using computer models with minimal attempt to investigate observed feedbacks. Recent studies have made initial attempts to quantify the impacts of vegetation variability on climate using observed data. One of these studies assessed observed vegetation feedbacks on surface air temperature and precipitation across the United States using satellite-derived vegetation data and observed monthly climate data for 1982-2000. The results show that an increase in vegetation generally leads to a substantial increase in temperature across the northern states, particularly in the spring. The impact of vegetation on precipitation appears to be more complex and relatively weak. It appears that an increase in vegetation over the major croplands of the United States supports an increase in precipitation. Figure 7 illustrates these responses.

Understanding and Modeling Ocean Mixing Processes.[7,15,25,46] Ocean mixing processes that are too small to be explicitly included in current climate models are an important area of research, since these processes largely determine the rate of heat uptake by the ocean. Two U.S. Climate Variability and Predictability (CLIVAR) Climate Process and Modeling Teams (CPTs), supported by NSF, NOAA, and NASA, have focused on improving the understanding and representation of ocean mixing processes in climate models. One CPT is working on how to include in climate models the ocean mixing that results when dense waters flow over steep ocean bottom features, mixing with overlying waters. One region where this occurs is in the North Atlantic (see the research highlight above on "Declining North Atlantic Salinity") where waters from the Arctic region sink and pass south into the Atlantic and help form the meridional overturning circulation. Comparisons of modeling approaches have been completed and evaluations of new treatments of these processes in the models are underway. The second ocean CPT is studying the transfer and mixing of ocean properties by small upper ocean features. These small eddies transport large amounts of heat in the Southern Ocean and in the Gulf Stream and Kuroshio Current regions and modulate the exchange of heat between the ocean and atmosphere in these regions. A recent study shows that "salt fingers," or filaments of salty water that sink in the ocean, play a more important role in vertical mixing of ocean waters than previously thought.

Projected Changes

The following highlights illustrate recent studies that have projected potential changes in future climate conditions based on simulations by state-of-the-art computer models.

Rainfall Extremes.[18,55] A set of recent modeling studies using the archived results of the IPCC Fourth Assessment Report models indicates that what would be considered a rare weather event at present may become commonplace by the end of this century. Furthermore, these rare events may increase in severity far more than changes in annual average conditions. For example, one study indicates that rainfall on the wettest day of the year is likely to increase more than changes in the average annual rainfall under conditions of increased greenhouse gases. Changes in such rainfall extremes may have larger impacts on the environment and society than changes in average annual rainfall. The results also suggest that the signature of greenhouse gas increases may be identified more easily from changes in extreme rainfall than changes in average rainfall.

CLIMATE MODEL EVALUATION, DIAGNOSIS, AND IMPROVEMENT

Recent advances in climate model evaluation and diagnostics include the use of both improved coupled climate models and new diagnostic techniques, and case studies of particular climate events—for example, the 1997-1998 El Niño. Researchers are working in a multi-faceted manner to improve climate model simulation on a hierarchy of time scales using a variety of different approaches. The information learned from these studies at all relevant time scales is being infused into the model development process. In this way, important processes that contribute to essential climate feedbacks are being addressed in a manner consistent with the recommendations made by the National Research Council in its report *Understanding Climate Change Feedbacks*. Examples of this work are provided below.

Weather Time Scale
Running climate models in weather forecast mode continues to yield useful insights. Many errors in the climate simulated by the model are the result of errors found in the short-range forecasts, making their diagnosis and improvement in this framework tractable. One such problematic aspect of many climate models is representation of the day-night (diurnal) cycle of precipitation over land. Detailed diagnostics of model simulations have been performed at the Atmospheric Radiation Measurement (ARM) Southern Great Plains site. At this site, ARM data can be used to diagnose the effects of large-scale circulation and moist processes on the diurnal characteristics of temperature and moisture.

Intraseasonal Time Scale
The Madden-Julian Oscillation (MJO) dominates tropical variability at time scales of 30 to 70 days. During the boreal winter and spring, it manifests as an eastward propagating disturbance that affects convection (rainfall) over much of the tropical eastern hemisphere. The MJO is a critical test of the ability of a climate model to correctly simulate tropical variability that most models fail to accurately represent. An improved representation of the MJO should contribute to improved medium-range and seasonal forecasts over the tropics, and possibly the extratropics. Recent analyses of models and observations indicate that simulating a realistic basic state is at least as important as air-sea interaction for producing the MJO. Additional recent analyses found that the Southeast Asian summer monsoon must be considered as a mutually interactive system with the MJO. By doing so, the onset of conditions that suppress convection (break the monsoon) over India may be detected 5 to 10 days earlier than had been previously suggested.

Interannual Time Scale
A recent study used the 1997-1998 El Niño as a test case to analyze cloud-climate interactions in a state-of-the-art climate model. This climate event was characterized by a drastic change in the tropical Pacific's atmospheric circulation, with corresponding anomalies in cloud altitudes. The study found that the model reproduced these changes well, including changes in the east-west structure of clouds. Another recent study examined the structure of warm season hydroclimate variability over the U.S. Great Plains—a region of profound importance for U.S. agriculture—and the extent to which the observed variability features are represented in state-of-the-art climate model simulations. The study found that remote water-vapor sources play an important role in generating interannual variability in the observed Great Plains summer hydroclimate. The tested models, however, largely depend on anomalies in local evaporation (precipitation recycling) to generate this variability. Further understanding of the source of the models' spurious evaporation is needed before they can be confidently used for regional hydroclimate simulations and predictions.

Centennial Time Scale
Climate modeling groups around the world performed an unprecedented set of coordinated 20th- and 21st-century climate change experiments in 2004 and early 2005, in addition to greenhouse gas stabilization experiments extending to the 22nd century (see description later in this chapter), for the IPCC Fourth Assessment Report. The resulting multi-model data set is a unique and valuable resource for international scientists to assess model performance, model sensitivity, and model response to a variety of factors related to 20th-, 21st-, and 22nd-century climate and climate change. Convenient and rapid access to this data set is provided through a specially configured web portal at the Program for Climate Model Diagnostics and Intercomparison, which includes a catalog and an interface to the archive. Over 300 projects using the archive have been registered, and over 200 manuscripts have been submitted for publication to date. The CCSP-sponsored Climate Model Evaluation Project (CMEP) supported more than 20 projects specifically to analyze the models' ability to simulate features of 20th-century climate. The list of publications that has resulted from the CMEP activity is available at <www.usclivar.org/CMEP_awards.html>.

Refer to chapter references 1,5,16,29,32,33,36,39,43,49,51,57,58 for more detail.

Estimating Future Changes in Permafrost.[24] Analysis of 21st-century climate change simulations with a state-of-the-art climate model (Community Climate System Model, CCSM3) has shown that areas of permafrost may greatly decrease over the course of the 21st century, with the area of decrease proportional to the amount of warming, which in turn depends in part on the emissions scenario used in the model. Such large changes in permafrost may provoke positive feedbacks such as activation of the soil carbon pool and a northward expansion of shrubs and forests.

Tropical Ocean Response to Global Warming.[27,52] Many studies have suggested that tropical Pacific SSTs are most likely to respond to global warming with an El Niño-like pattern, characterized by stronger warming in the east than in the west. However, a new finding from the most recent IPCC model simulations as well as past climate records challenges this traditional view. A recent study suggests that the most robust fingerprint of tropical Pacific SSTs in response to global warming is the so-called Enhanced Equatorial Response, characterized by an enhanced equatorial warming relative to the subtropics (Figure 8a). In comparison, the east–west difference in equatorial SSTs shows little systematic long-term change (Figure 8b). This new finding calls for a rethinking of the mechanism for tropical ocean response to global warming.

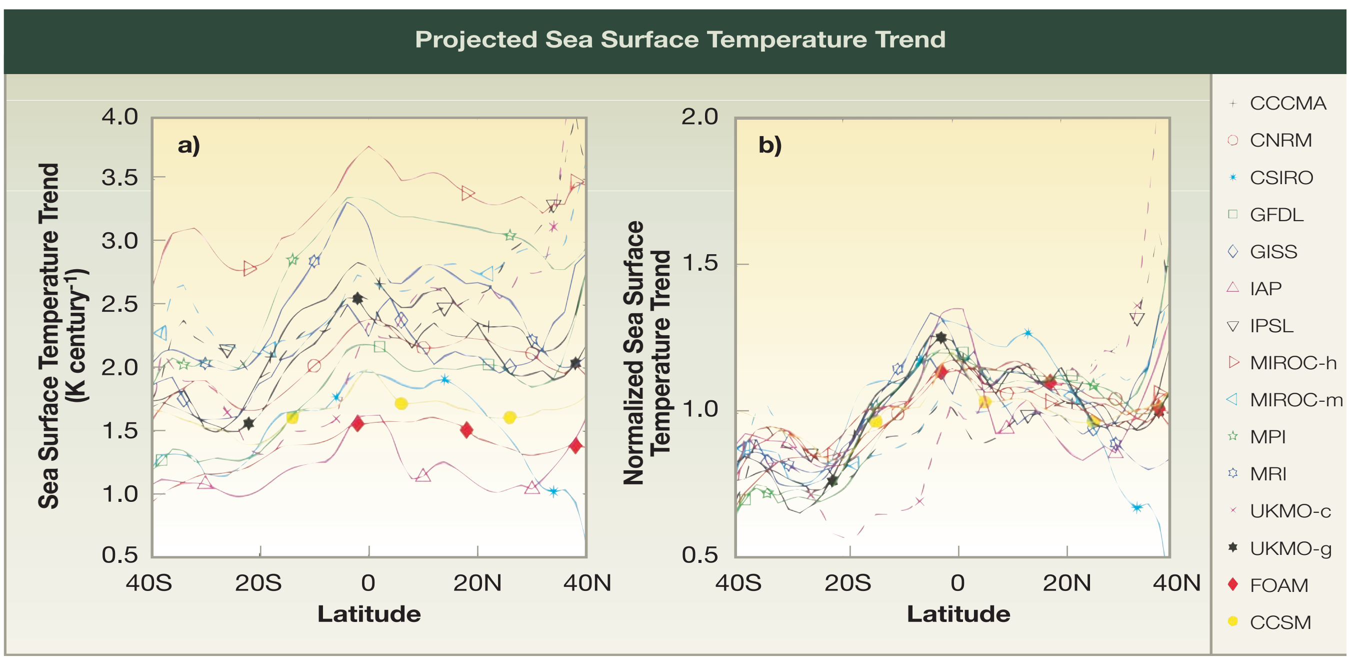


Figure 8: Projected Sea Surface Temperature Trend. Trends of Pacific sea surface temperature in IPCC model simulations driven by a transient increase in atmospheric CO_2 concentration. (a) Sea surface temperature trend averaged across the Pacific at each latitude between 40S and 40N, showing general agreement among models for enhanced equatorial warming. (b) As in (a), but with each model's temperature trend divided by each model's mean trend over the Pacific Ocean, showing the robustness of the enhanced equatorial warming across the models regardless of their individual climate sensitivities. *Credit: Z. Liu, University of Wisconsin (reproduced from the* ***Journal of Climate*** *with permission from the American Meteorological Society).*

DETECTION AND ATTRIBUTION OF CLIMATE CHANGE

Two related sets of issues being addressed by CCSP are the extent and causes of recently observed changes. Research on the extent, as well as the characteristics of climate change (i.e., detection), is based on analyses of observational data from both *in situ* and remotely sensed sources and comparison with historical and proxy records. Research on the causes of climate change (i.e., attribution) is based on focused modeling and process studies. The modeling studies often use estimates of historical changes in human-caused and natural external forcings (i.e., factors that may cause climate change such as greenhouse gases, solar output, volcanic eruptions, and dust particles) to assess the relative contributions of the various forcings to the observed changes. Early analyses of this type focused primarily on globally averaged surface temperature during the past century. However, recent CCSP work has utilized a much wider range of variables and has explored a variety of new analytical techniques. Some of the climate variables that have been analyzed include regional temperature extremes, African drought, atmospheric pressure, ocean temperature, precipitation, and upper atmospheric temperature. Examples of results from some of these studies are outlined below.

European Heat Wave

The summer of 2003 was probably the hottest in Europe since at least AD 1500, and unusually large numbers of heat-related deaths were reported in France, Germany, and Italy. It is not possible to definitively determine whether the 2003 heat wave was caused by, for example, increasing atmospheric concentrations of greenhouse gases, since almost any such weather event might have occurred by chance in an unmodified climate. However, it is possible to estimate how much human activities may have increased the risk of the occurrence of such a heat wave. Using a threshold for mean summer temperature that was exceeded in 2003, but in no other year since the start of the instrumental record in 1851, a modeling study recently concluded that it is very likely (confidence level >90%) that human influence has at least doubled the risk of a heat wave exceeding this threshold magnitude. Model projections of future climate change indicate that summers as warm as that of 2003 in Europe are likely to be typical by 2040.

African Drought

Two recent studies have strongly implicated long-term variations in ocean conditions in producing prolonged drought conditions in the Sahel and portions of central Africa during the latter part of the 20th century. One study analyzed 80 separate 50-year climate simulations from a suite of climate models in which the only external driving force was observed SST. The results showed a very robust response across all models in reproducing the observed precipitation patterns over Africa during this period. The drying over the Sahel during boreal summer was shown to be a response to warming of the South Atlantic relative to the North Atlantic during this period, which favored a southward shift of the ITCZ and accompanying rainfall. That study also evaluated a set of greenhouse gas-forced experiments conducted for this period as part of the IPCC Fourth Assessment Report. The authors found that, while there were considerable differences among the model simulations, the majority were unable to simulate either the pattern or amplitude of the 20th-century African drying, leading them to conclude that the observed, sustained African drought conditions were most likely due to long-period, natural variations in Atlantic ocean conditions, rather than to greenhouse gas forcing.

A second study with a coupled climate model forced with greenhouse gases was, however, able to reproduce much of the observed African precipitation variability. As in the first study, Atlantic SST variations were found to be important in causing the Sahelian drought, but in this model, the SST changes resulted largely from changes in the north-south distribution of aerosols during this period. The authors of this second study suggested that anthropogenic as well as natural factors might have caused the 20th century Sahelian drought. Because of the wide range of coupled model projections of future SST distributions in the North and South Atlantic, projections of future precipitation in this region remain uncertain. These studies and others reinforce the need for improved understanding of sources of variability in the world oceans to increase confidence in projections of future regional climate changes.

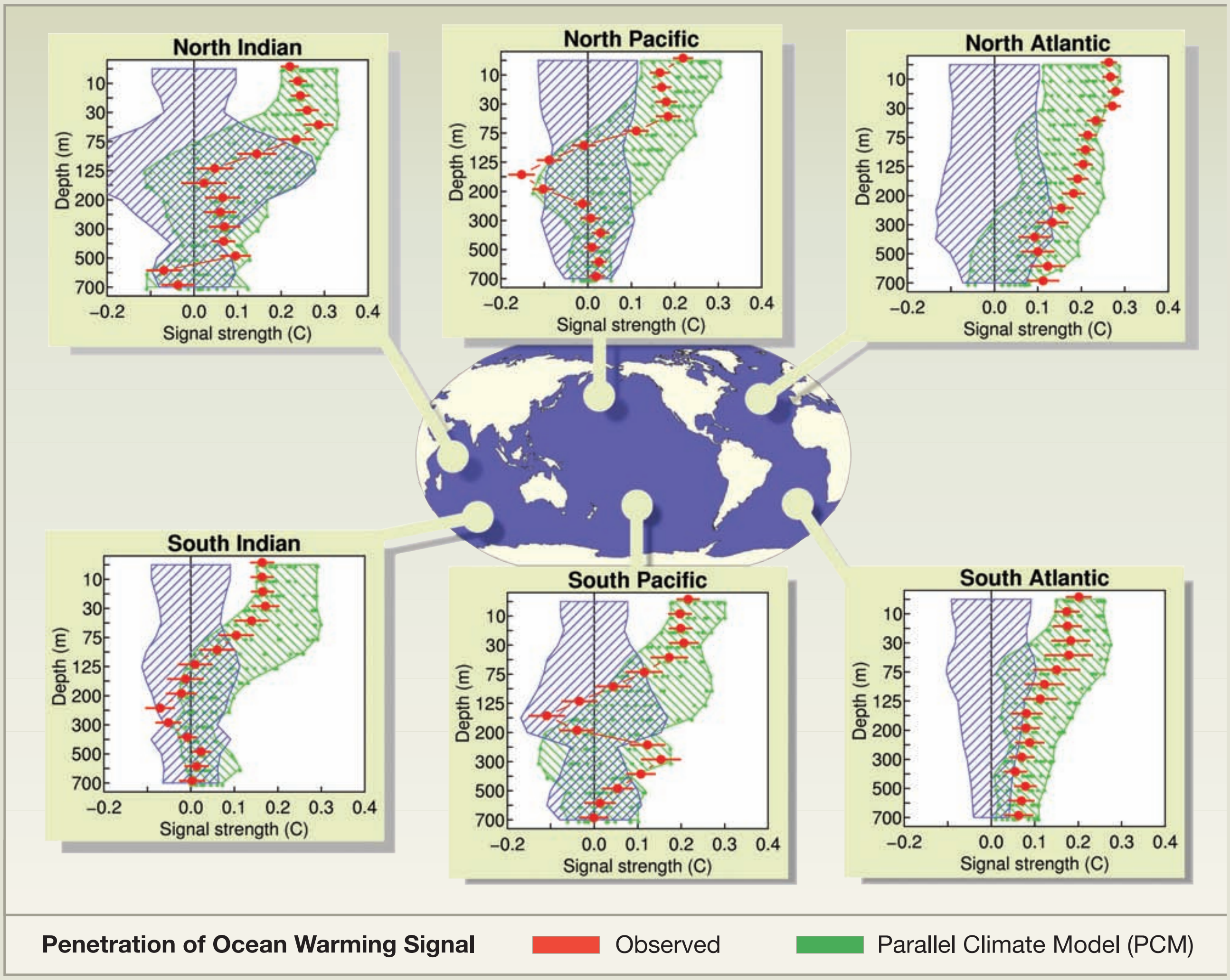
North American Droughts and Wet Periods

Recent research suggests that subtle, prolonged changes in SSTs in the tropical oceans, especially in the tropical Pacific Ocean, may have been responsible for prolonged North American droughts and pluvials (extended periods of abundant rainfall) in the 19th and 20th centuries. This new work highlights links between decadal variability of tropical Pacific SSTs and major, high-impact events such as the 1930s Dust Bowl drought, drought in the 1950s, the pluvial period in the late 20th century in the western United States, and the return to drought in this region after 1997. The relationships were investigated using a large ensemble of 145-year climate model runs.

Ocean Temperature

Observations show that approximately 84% of the total heating of the Earth system (oceans, atmosphere, continents, and cryosphere) over the last 40 years has gone into warming the oceans. A recent study on the vertical structure of ocean warming trends over the past 40 years

DETECTION AND ATTRIBUTION OF CLIMATE CHANGE (CONTINUED)



Warming Signal by Ocean/Depth. Anthropogenic forcing signal strength (green hatched region) compared to that obtained from observations (red dots). There is excellent agreement at most depths in all oceans. The hatched region shows the range of the signal strength estimates from five different realizations of identically forced simulations with the Parallel Climate Model. *Credit: D. Pierce, Scripps Institution of Oceanography (reproduced with permission from* **Science***).*

in various basins compared trends in climate model simulations with trends based on an updated ocean temperature data set. The warming signal is complex, with a vertical structure that varies widely by ocean. It cannot be explained by natural internal climate variability or solar and volcanic forcing, but is relatively well simulated by two anthropogenically forced climate models (see accompanying figure).

Another study examining the warming in the oceans over the last century suggests that, in addition to greenhouse gases, aerosols (tiny airborne particles) have played a significant role during this period. Aerosols may have delayed the onset of warming by several decades and reduced the magnitude of the warming by approximately two-thirds when compared to the response arising solely from increasing greenhouse gases.

Refer to chapter references 2,3,8,12,17,19,21,22,26,47,50 for more detail.

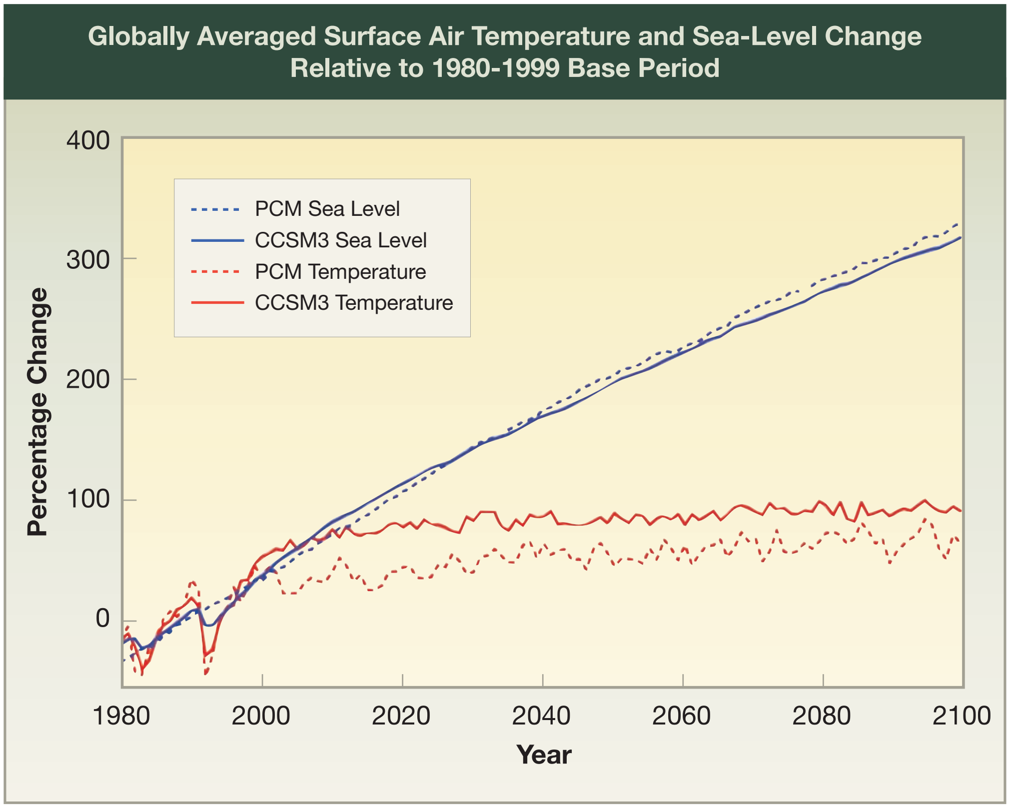


Figure 9: Globally Averaged Surface Air Temperature and Sea-Level Change Relative to 1980-1999 Base Period. Results from two state-of-the-art climate models (the Parallel Climate Model and the Community Climate System Model) in which greenhouse gas concentrations are stabilized at the end of the 20th century. Temperature and sea-level values are shown relative to the averages for the base period, 1980-1999. *Credit: J. Arblaster, National Center for Atmospheric Research (reproduced with permission from* **Science***).*

Climate Model Studies with Static Greenhouse Gas Concentrations.[34] A greenhouse gas stabilization experiment performed with two global climate models (the Parallel Climate Model and the CCSM3) shows that even if concentrations of greenhouse gases could be stabilized at present-day values, the thermal inertia of the climate system would lead to further warming, and ongoing sea-level rise due to thermal expansion of seawater. These modeling results indicate that if greenhouse gas concentrations were stabilized at present levels, by 2100 sea level may rise about three times the amount that has already been observed (see Figure 9), with continued sea-level rise for a few subsequent centuries.

HIGHLIGHTS OF FY 2007 PLANS

Development of Integrated Earth System Analysis Capabilities. Research across several agencies will focus on supporting the development of a national capacity to provide integrated Earth system analyses, in order to provide an ongoing, near-real-time basis for assessing the state of the global Earth system. Initially, these analyses will be performed at a variety of temporal and spatial scales and with different degrees of coupling between components of the Earth system (e.g., carbon cycle, ocean, water cycle, ecosystems). In future years, as observing systems and models improve, this capacity will be supported by periodic integrated Earth system reanalyses to serve as the Nation's best assessment, or "analysis of record," of how the Earth system has varied over the recent historical period. These efforts will directly support vitally important scientific linkages between current and proposed future Earth observation systems and Earth system modeling capabilities.

These activities will address Goals 1 and 2 of the CCSP modeling strategy, Goal 4 of the CCSP observing and monitoring strategy, and Questions 4.1 and 4.2 of the CCSP Strategic Plan.

Modern Era Retrospective-analysis for Research and Applications (MERRA). MERRA is a specific example of the work being conducted on the priority item mentioned above: development of integrated Earth system analysis capabilities. The purpose of the MERRA project is to develop, validate, and disseminate a global retrospective analysis data set, covering the modern era of remotely sensed data from 1979 through the present. The special focus of the atmospheric assimilation project will be the hydrologic cycle. This project is expected to take 2 years to complete (see <gmao.gsfc.nasa.gov/research/merra>).

This activity will address Goals 1 and 2 of the CCSP modeling strategy and Questions 4.1 and 4.2 of the CCSP Strategic Plan.

Carbon Data Assimilation (CDA). Another specific example of integrated Earth system analysis work is a 5-year effort to develop a coupled Earth system assimilation model for carbon and ecosystems. The first stage commenced in FY 2006, when a NASA atmospheric model (GEOS5) together with a NOAA assimilation scheme was installed on computers at the Oak Ridge National Laboratory to begin testing. The GEOS5 model is compliant with Earth System Model Framework standards, which is important for exchanging and intercomparing model elements. This activity is part of DOE's National Leadership Computing Facility (NLCF) Climate End Station climate and carbon research. Future plans include coupling several different ocean models to

the GEOS5 atmosphere, as well as to a dynamic ecosystem model. With launch of the NASA Orbiting Carbon Observatory (OCO) satellite scheduled in 2008, this model integration and evaluation will improve the characterization of carbon sources and sinks.

These activities will address Goals 1, 2, and 3 of the CCSP modeling strategy, Goal 2 of the CCSP Strategic Plan, and Questions 3.5, 4.1, 4.2, and 7.5 of the CCSP Strategic Plan.

Earth System Response to Climate Change and Variability. Research will be conducted on the response of terrestrial, wetland, estuarine, and marine systems to climate changes at seasonal to millennial time scales using paleoclimatic proxies of past climate variability. These process-based studies are designed to understand the physical, biological, and chemical impacts of different climate regimes, as well as leads and lags between different climate events and Earth system responses. Paleoclimatic observations provide insights into mechanisms governing climate change and variability at regional to global scales and key information to improve predictions of future Earth system response to a variety of climate and environmental changes. These data will also provide a context for evaluating data generated through emerging integrated Earth system analysis capabilities.

These activities will address Goals 1 and 4 of the CCSP Strategic Plan and Questions 4.2, 4.3, 4.4, and 8.2 of the CCSP Strategic Plan

Database of Arctic Climate Variability. A new database will be completed of Arctic climate variability derived from paleoclimate proxies spanning the past 2,000 years. The project synthesizes the results of dozens of studies funded by NSF and other sources, with the aim of reconstructing long-term variations in Arctic temperature, as well as reconstructing the natural variability that exists in temperature, precipitation, sea-ice extent, surface pressure, and other environmental parameters over shorter time periods (see <www.ncdc.noaa.gov/paleo>).

This activity will address Goal 1 of the CCSP Strategic Plan and Questions 4.1, 4.2, 4.3, and 4.4 of the CCSP Strategic Plan

New Integrated Ocean Drilling Program to Obtain High-Resolution Climate Records. The first phase of the Integrated Ocean Drilling Program produced high-resolution records of climate over past millennia from marine sediments. Recent examples include the first recovery of central Arctic Ocean marine sediment records and expeditions to drill methane hydrates, which may have been a cause of past abrupt climate change. The Integrated Ocean Drilling Program will enter a new phase of operations in FY 2007 with a major refit and conversion of the JOIDES *Resolution*, a dedicated scientific ocean drilling vessel used for recovering sequences of sediment and rock cores from global ocean basins (depicted in Figure 10). When the refit and conversion is complete, the international research community will have a multi-platform marine drilling capability, including the *Resolution* (a light drill ship) and the *Chikyu* (a heavy drill ship provided by Japan), to retrieve new and longer records of climate change from the deep seafloor in a new era of scientific drilling. Rapidly accumulating marine sediments remain the longest, most continuous record of past climate and environmental variability found on the planet and will be explored by the *Resolution*.

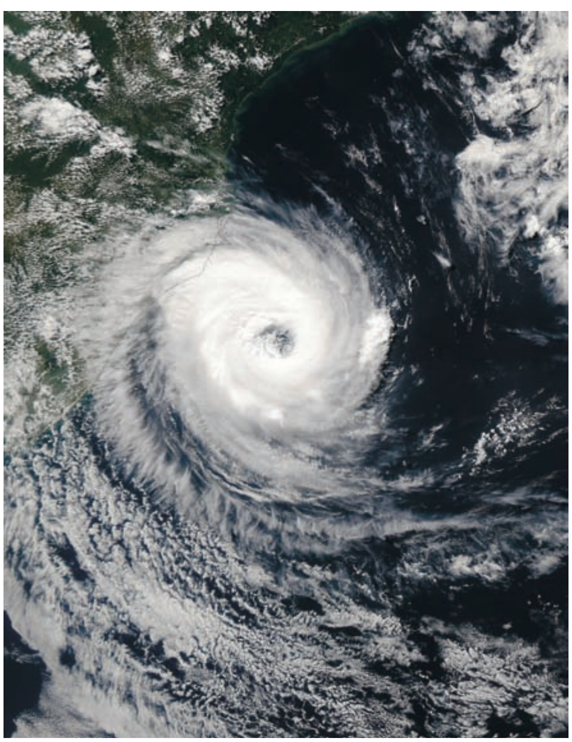
This activity will address Goals 2 and 5 of the CCSP observing and monitoring strategy and Question 4.3 of the CCSP Strategic Plan.

Figure 10: Integrated Ocean Drilling Platform. The dedicated JOIDES *Resolution* scientific drilling vessel used for recovering sequences of sediment and rock cores from global ocean basins. *Credit: D. Anderson, NOAA/National Geophysical Data Center.*

NARCCAP Data Analysis Phase. The North American Regional Climate Change Assessment Program (NARCCAP) is part of a U.S.-Canadian/European collaborative regional climate modeling study. NARCCAP's primary objective is to develop, and make openly available, multiple high-resolution regional climate change scenarios for use in impact and risk assessments. Analyses of the scenarios, with a focus on North America, will be conducted in FY 2007 to: (1) understand critical regional climate change issues, such as the effects of increased greenhouse gases on the frequency of various types of extreme weather events; (2) enhance understanding of key issues in regional climate modeling, including methodological approaches; (3) conduct a limited examination of uncertainties in regional and global climate model projections; and (4) create greater collaboration between U.S., Canadian, and European climate modeling groups to leverage the diverse modeling capability across these nations.

These activities will address Goals 4 and 5 of the CCSP Strategic Plan and Questions 4.3 and 4.4 of the CCSP Strategic Plan.

Reducing Tropical Errors in Climate Models. A multi-institutional project will continue in FY 2007 to attempt to reduce errors in the tropics in coupled ocean-atmosphere general circulation models. These errors affect the average SST and precipitation as well as the structure and distribution of climate variability throughout the tropics, and must be significantly reduced for coupled general circulation models to realize their potential for climate prediction. This project began with an initial workshop held at NOAA's Geophysical Fluid Dynamics Laboratory in 2003 and a second workshop at the Center for Ocean-Land-Atmosphere Studies (COLA) in 2005. At the COLA workshop, several experiments were agreed on, and progress was reviewed in June 2006 at the annual Community Climate System Model workshop. Descriptions of the first and second workshops and ongoing work are available at <www.iges.org/ctbp>.



These activities will address Goal 1 of the CCSP modeling strategy and Goal 1 of the CCSP Strategic Plan.

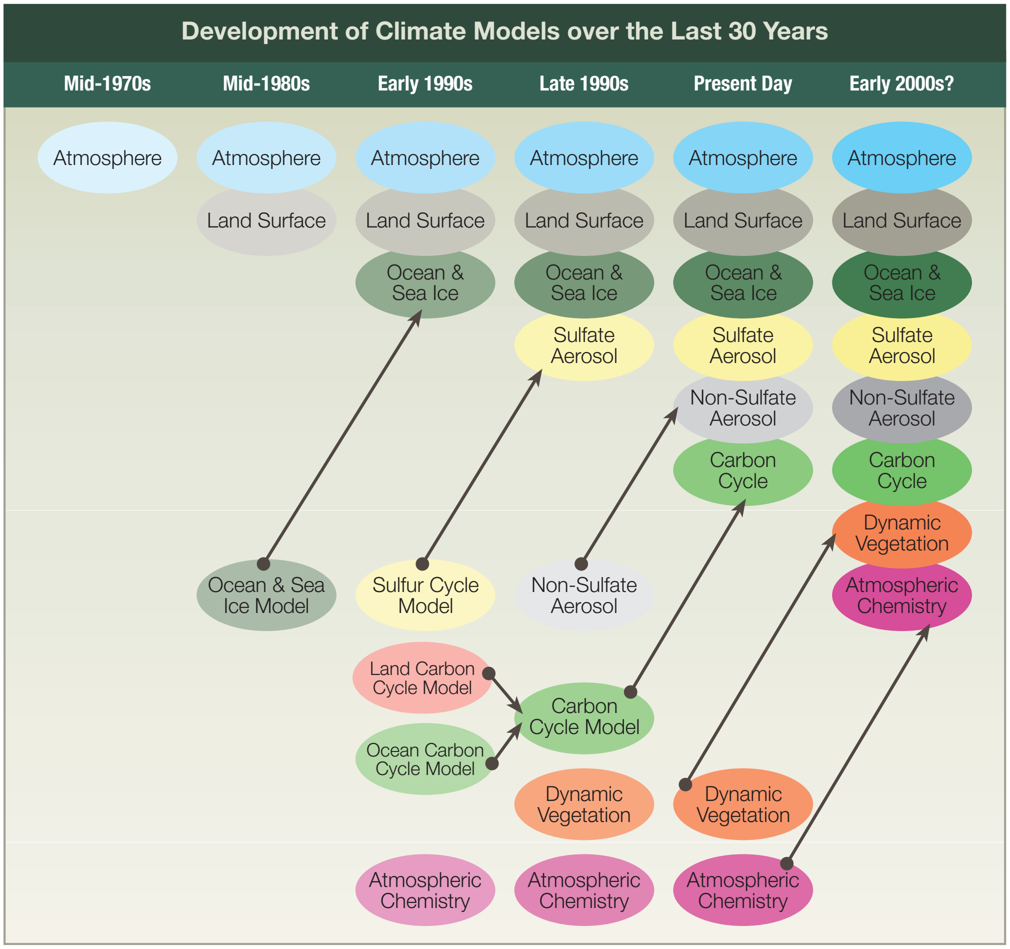
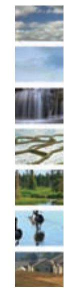


Figure 11: Development of Climate Models over the Last 30 Years. The development of climate models over the last 30 years showing how the different components are first developed separately and later coupled into comprehensive climate models. *Credit:* **CCSP Strategic Plan**, *Chapter 10 (2003).*

Development of the Next Generation of Climate System Models. In parallel with continued research on the physical representations of climate processes, particularly in the tropics, climate model development will concentrate on improving representations of aerosols, atmospheric chemistry, the carbon cycle, land surface-atmospheric processes, and middle-atmosphere dynamics and chemistry (Figure 11 describes the development of climate models over the past 30 years). The products will be next-generation climate system models with enhanced capabilities to model more comprehensively the interactive physical, chemical, and biological components of the climate system. This work will continue over the longer term, leading to fully interactive Earth system models.

These activities will address Goal 1 of the CCSP modeling strategy,
Goals 1, 2, and 3 of the CCSP Strategic Plan,
and Questions 4.1 and 4.2 of the CCSP Strategic Plan.



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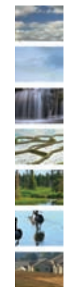


3 | Global Water Cycle

Strategic Research Questions

5.1 What are the mechanisms and processes responsible for the maintenance and variability of the water cycle; are the characteristics of the cycle changing and, if so, to what extent are human activities responsible for those changes?

5.2 How do feedback processes control the interactions between the global water cycle and other parts of the climate system (e.g., carbon cycle, energy), and how are these feedbacks changing over time?

5.3 What are the key uncertainties in seasonal to interannual predictions and long-term projections of water cycle variables, and what improvements are needed in global and regional models to reduce these uncertainties?

5.4 What are the consequences over a range of space and time scales of water cycle variability and change for human societies and ecosystems, and how do they interact with the Earth system to affect sediment transport and nutrient and biogeochemical cycles?

5.5 How can global water cycle information be used to inform decision processes in the context of changing water resource conditions and policies?

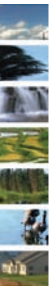
See Chapter 5 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of these research questions.

The global water cycle plays a critical role in the functioning of the Earth system. Through complex interactions, the global water cycle integrates the physical, chemical, and biological processes that sustain ecosystems and influence climate and related global change. Inadequate understanding of the water cycle is one of the key sources of uncertainty in climate prediction. Clouds, precipitation, and water vapor produce feedbacks that alter surface and atmospheric heating and cooling rates, leading to adjustments in atmospheric circulation and precipitation patterns—processes current climate models do not adequately represent. Improved understanding of these processes will be essential to developing options for responding to the consequences of water cycle variability and change. For these reasons, water cycle research is a high-priority area for near-term activities within CCSP.

Priorities in FY 2007 include the planning and implementation of integrated projects to aggressively accomplish the *CCSP Strategic Plan* goals for water cycle research. As part of this process, the CCSP-participating agencies involved in the global water cycle research element are defining a program of activities that will produce the kinds of interdisciplinary breakthroughs that the water cycle science community has identified as essential. These activities are organized around the need for comprehensive coincident measurements of all aspects of the water cycle, including atmospheric, surface, and subsurface observations. Observational data sets that capture key features of the water cycle at the same place and time promise to improve estimates of key fluxes and stores within the linked water and energy cycles, which are needed to balance water and energy budgets. In addition, long-term records of water cycle variables are vital for assessing changes in the Earth system. Strategies for implementation include assembling long-term data sets of water cycle variables, including new tools and techniques, reanalysis of existing records, assimilation of observations and model output, and establishment of a network of observation stations with new capabilities for collecting and integrating data for interdisciplinary research. In addition to addressing CCSP goals, these ongoing and planned observations will support the objectives of the Global Earth Observation System of Systems (GEOSS) and its U.S. counterpart, the International Earth Observing System (IEOS).

The global water cycle research element continues to pursue important, long-term priorities. For example, insights into the formation and behavior of clouds and precipitation, including better characterizations of the phase changes of water in clouds and the phases and onset of precipitation, are emerging from field campaigns and model studies and will be promoted in continuing activities. Similarly, the predictability of regional precipitation will be assessed and better understood by ongoing diagnostic and modeling studies that identify the connections between regional- and global-scale phenomena, land-surface conditions (such as soil moisture), and rainstorms. Results from these studies show promise of leading to earlier (and more accurate) predictions, improved ability to assess hazards and risks of extremes such as floods and droughts, and more efficient water resource management. In this context, the results of advances in coupled ocean-atmosphere-land models will be important.

The ultimate goal of this water cycle research is to provide a better foundation for decisions and investments by policymakers, managers, and individuals. Achieving this goal requires a program of activities that tests predictions and data products in real decisionmaking contexts, demonstrates techniques and their effectiveness to potential users, and provides tools and strategies to transfer the science from the experimental realm to operations. Implementation of the *CCSP Strategic Plan*'s global water cycle research strategy addresses these issues.



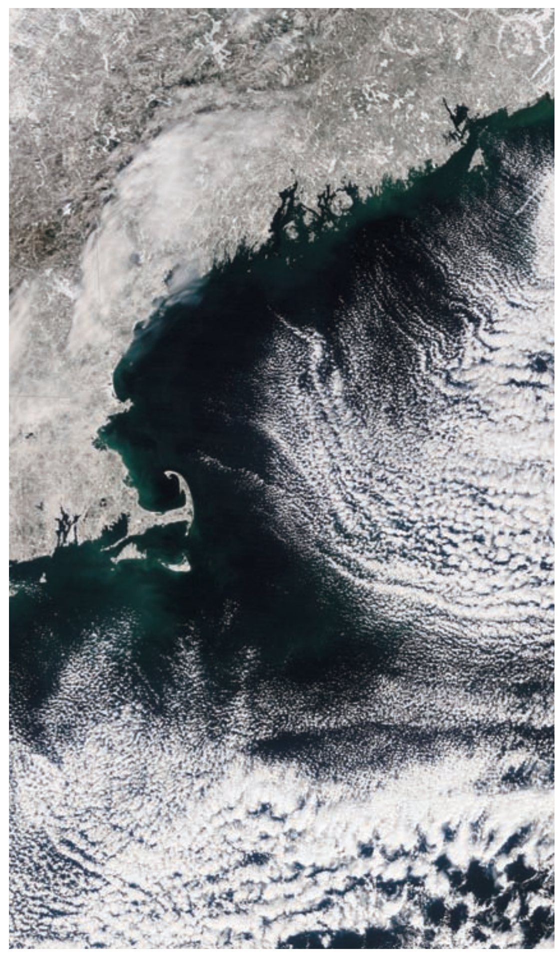
HIGHLIGHTS OF RECENT RESEARCH

Selected highlights of recent research supported by the CCSP-participating agencies follow. These research results address the strategic research questions on the global water cycle identified in the *CCSP Strategic Plan*. Due to the overlap between the global water cycle and other CCSP elements, some themes such as water vapor-radiation feedback, an important component of global water cycle research, are elaborated in other chapters of this publication rather than here.

Modeling and Simulation of Cloud Processes and Cloud Systems.[11,12,15,18,23]

Multi-Scale Simulations of Clouds. Researchers have been experimenting with a global atmospheric model in which the conventional cloud parameterizations are replaced, in each grid column, by a two-dimensional cloud-resolving model. Figure 12 shows that the model produces a simulation of upper tropospheric cloudiness that is much more realistic than a control run.

New Shallow Cloud Convection Scheme. By comparing regional model simulations with the observations collected at the Atmospheric Radiation Measurement (ARM) Southern Great Plains and Tropical Western Pacific sites, scientists evaluated the overall performance of a recently developed shallow cumulus parameterization scheme



Simulations and Observations of the High-Level Cloud Fraction

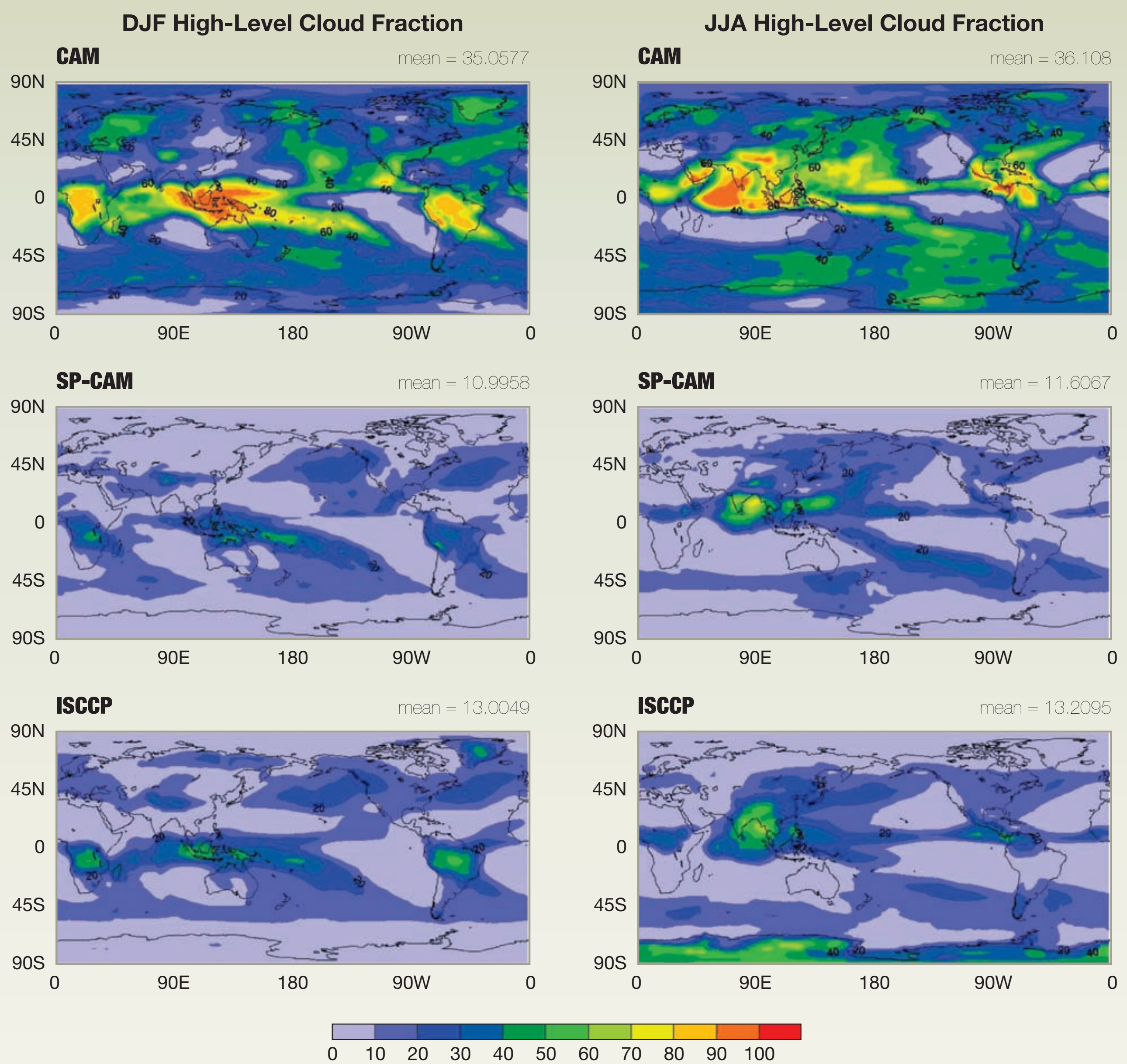


Figure 12: Simulations and Observations of the High-Level Cloud Fraction (above 400 mb). The left panels show results for December–February (DJF), and the right panels for June–August (JJA). The top two panels are from a control run (CAM); the middle two panels are from the experimental model (SP-CAM); and the bottom two panels show observations from the International Satellite Cloud Climatology Project (ISCCP). *Credit: M. Khairoutdinov, D. Randall, and C. DeMott, Colorado State University (reproduced from* **Journal of the Atmospheric Sciences** *with permission from the American Meteorological Society).*

under different meteorological conditions (see Figure 13). The simulations indicate that the shallow cumulus scheme can accurately simulate both marine shallow cumuli and the observed diurnal cycle of continental shallow cumuli. Sub-grid cloud properties, the resolved thermodynamic structures, and the surface energy budget are simulated well by the model.

Diagnostic Simulations of Arctic Cloud Systems. Scientists used measurements made as part of the ARM Mixed-Phase Arctic Cloud Experiment (M-PACE) to evaluate the performance of the Community Atmosphere Model (CAM3) of the National Corporation for Atmospheric Research (NCAR), the Atmosphere Model (AM2) of NOAA's Geophysical Fluid Dynamics Laboratory, and the weather forecast model of

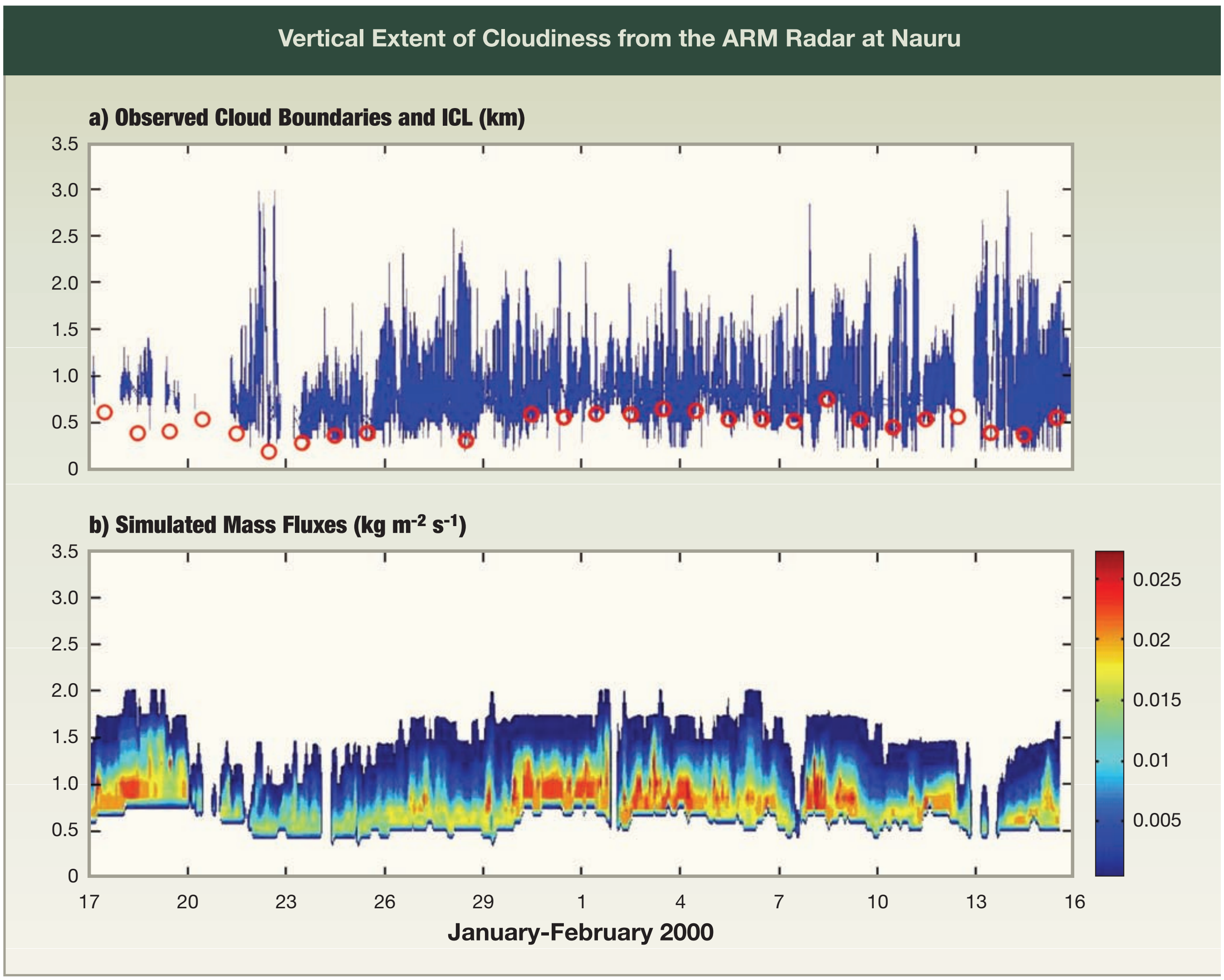


Figure 13: Vertical Extent of Cloudiness from the ARM Radar at Nauru. Time series of the vertical extent of cloudiness from the Atmospheric Radiation Measurement (ARM) radar at Nauru (top panel). Bottom panel shows the vertical distribution of the cumulus mass flux, which is an indicator of the vertical extent of the shallow cumulus clouds. *Credit: P. Zhu and C.S. Bretherton, University of Washington (reproduced from* **Monthly Weather Review** *with permission from the American Meteorological Society).*

the European Centre for Medium-Range Weather Forecasts (ECMWF) in simulating Arctic cloud systems. The two climate models were evaluated under the framework developed through a joint effort between DOE's Climate Change Prediction Program (CCPP) and the ARM program, the CCPP-ARM Parameterization Testbed, which is a diagnostic tool for evaluating climate models using weather prediction techniques. As revealed in the study, the models simulate the occurrence of clouds fairly well, but there are substantial errors in cloud microphysical properties. ARM data will be used to suggest improvements for these models (see Figure 14).

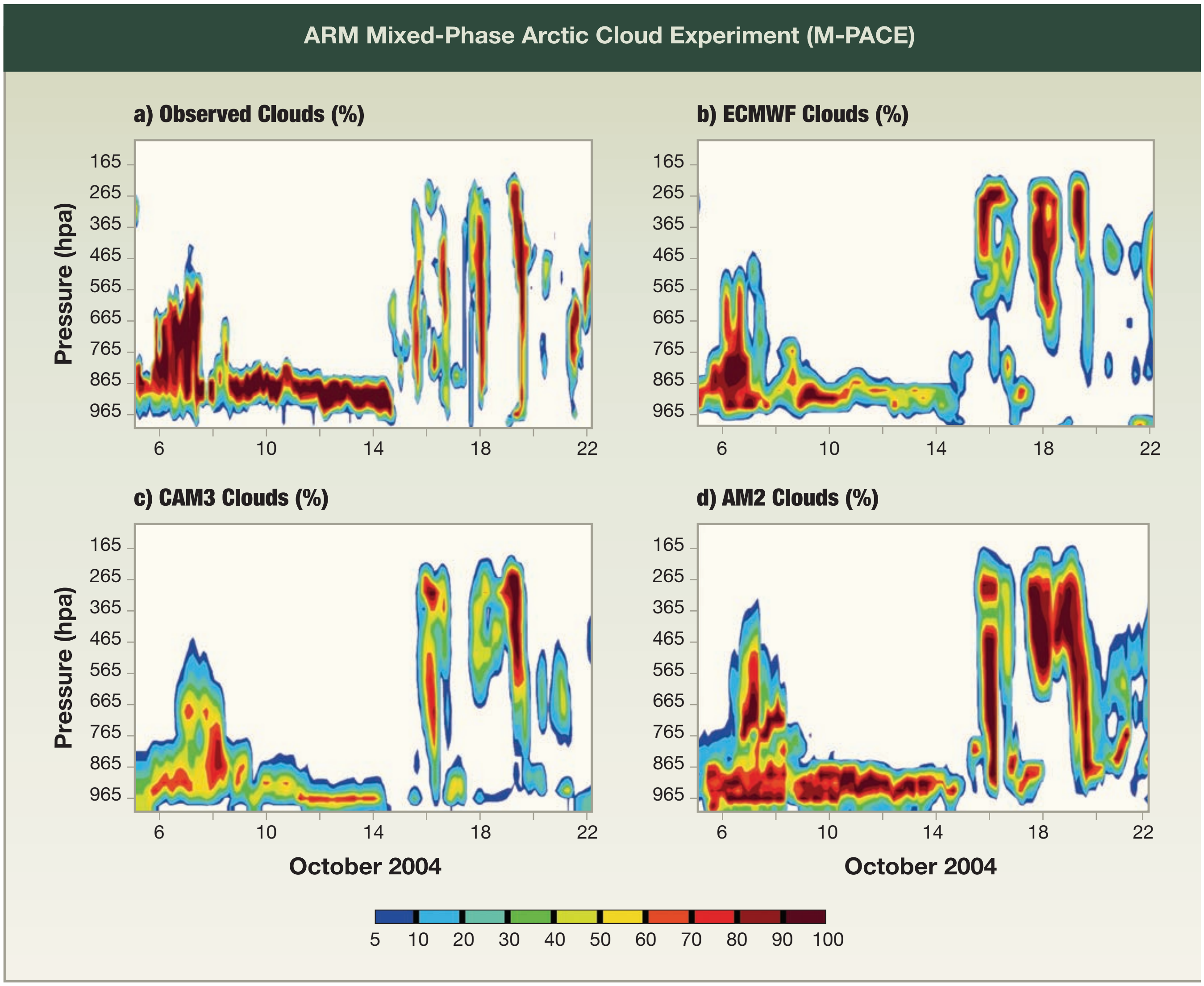
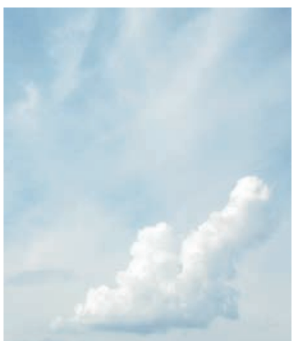


Figure 14: ARM Mixed-Phase Arctic Cloud Experiment (M-PACE). Temporal and vertical distribution of observed and simulated clouds from the European Centre for Medium-Range Weather Forecasts (ECMWF), CAM3, and AM2 at Barrow, Alaska, during the M-PACE periods. *Credit: S. Xie, Lawrence Livermore National Laboratory; S.A. Klein, Lawrence Livermore National Laboratory; J.J. Yio, Lawrence Livermore National Laboratory; A.C.M. Beljarrs, ECMWF; C.N. Long, Pacific Northwest National Laboratory; and M. Zhang, State University of New York, Stony Brook (reproduced from* **Journal of Geophysical Research** *with permission from the American Geophysical Union).*

New Model of Cloud Drop Distribution that Simulates Drop Clustering. CCSP scientists have developed size-dependent models of the spatial distribution of cloud drops that simulate the observed clustering of drops. Understanding of spatial distribution and small-scale fluctuations in cloud droplets is essential for both cloud physics and atmospheric radiation. For cloud physics, the coalescence growth of raindrops depends upon size distribution while, for radiation, the spatial distribution of cloud drops has a strong impact on cloud radiative properties. In contrast to currently used models that assume homogeneity and therefore a Poisson distribution of cloud drops, the new models show strong drop clustering, which increases with larger drop size. Clustering has vital consequences for rain physics, explaining how rain can form more quickly in the new models than simulations made with the former, homogenous models. The new models also help to explain why remotely sensed cloud drop size distributions are generally biased.



Improved Understanding and Modeling of Cloud Aerosol Interaction, Cloud Organization, and Radiative Properties.[17]

Studying Stratus, Radiation, Aerosol, and Drizzle. The DOE's ARM and Atmospheric Science Programs and the U.S. Office of Naval Research conducted a joint extensive field experiment at Pt. Reyes, California. The objectives were to collect data from cloud-aerosol interactions and to improve understanding of cloud organization that is often associated with patches of drizzle.

Simulating Radiative Properties of Ice Clouds. Scientists developed a model that provides a means of predicting the radiative properties of ice clouds in terms of explicit microphysical properties, such as the parameters describing a bimodal size distribution that accounts for the smallest ice crystals and the various ice crystal shapes in the size distribution. The ice radiative properties predicted by the model code are being used in a development version of the NCAR CAM/Community Climate System Model (CCSM), and it will be a candidate for inclusion in CAM4/CCSM4. The explicit coupling between ice particle microphysical properties and radiative properties also provides a better opportunity for investigating the role of aerosol-ice nucleation processes in global climate processes.

Percentage of Global Land Areas Affected by Serious Drought Increases.[2]
Global Palmer Drought Severity Index data and offline simulations with the NCAR land-surface model were used to study the potential drying over global land areas associated with the warming during the last several decades. This study found that the percentage of the global land area affected by serious drought more than doubled from about 15% during the 1970s to about 30% in the early 2000s. Widespread drying occurred over much of Europe and Asia, Canada, western and southern Africa, and eastern Australia. The warming-induced drying has occurred over most land areas with

Linear Trends in the Palmer Drought Severity Index (PDSI) from 1948 to 2002

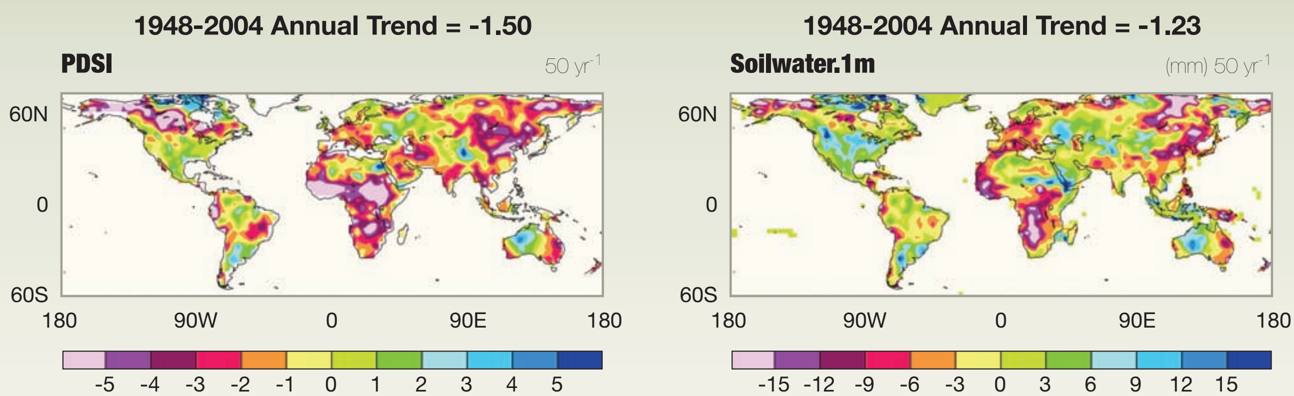


Figure 15: Linear Trends in the Palmer Drought Severity Index (PDSI) from 1948 to 2002. These data products show drying (reds and pinks) across much of Canada, Europe, Asia, and Africa and moistening (green) across the United States, Argentina, Scandinavia, and western Australia. *Credit: A. Dai, K.E. Trenberth, and T. Qian, National Center for Atmospheric Research (reproduced from* **Journal of Hydrometeorology** *with permission from the American Meteorological Society).*

the largest effects in northern mid- and high latitudes. In contrast, rainfall deficits alone were the main factor behind expansion of dry soils in Africa's Sahel and East Asia. Figure 15 illustrates these trends.

Mass Decrease in the Greenland Ice Sheet.[13,19,21] Greenland hosts the largest reservoir of freshwater in the Northern Hemisphere, and any substantial changes in the mass of its ice sheet will affect global sea level, the meridional overturning circulation of the ocean, and therefore the climate system. The Greenland glaciers cover an area of about 1.7 million km^2 (a little smaller than Mexico) and are up to 3-km thick in spots. In the first direct, comprehensive mass survey of the entire Greenland Ice Sheet, scientists using data from the NASA/German Aerospace Center Gravity Recovery and Climate Experiment (GRACE) measured a significant decrease in the mass of the Greenland ice cap resulting from a speeding up of the flow of Greenland glaciers and accelerated ice discharge. GRACE detected a volume reduction in the Greenland ice sheet of 162 ± 22 km^3 (39 ± 5.4 mi^3) per year between 2002 and 2005. This is higher than all previously published estimates, and represents a contribution of about 0.4 mm (0.016 in) per year to global

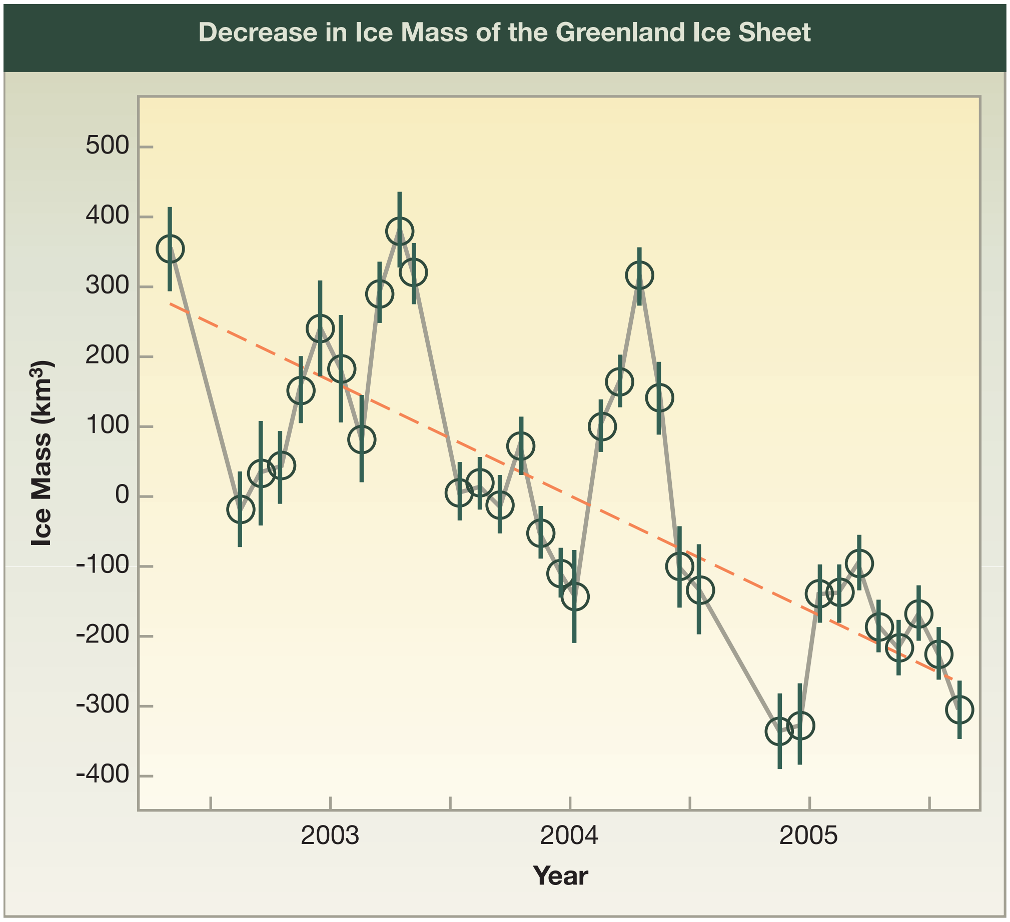
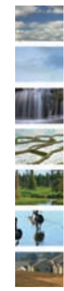


Figure 16: Decrease in Ice Mass of the Greenland Ice Sheet from mid-2002 to mid-2005. The rate of change over this period of GRACE monitoring represents a decrease of 162 ± 22 km^3 yr^{-1}, which contributes about 0.4 ± 0.1 mm yr^{-1} to sea-level rise. *Credit: I. Velicogna and J. Wahr, University of Colorado (reproduced from* **Geophysical Research Letters** *with permission from the American Geophysical Union).*

sea-level rise as shown in Figure 16. The identical twin GRACE satellites track minute changes in Earth's gravity field resulting from regional changes in Earth's mass such as masses of ice, air, water, and solid earth that shift due to weather patterns, seasonal change, climate change, and even tectonic events. GRACE has the unique ability to measure monthly mass changes for an entire ice sheet—a breakthrough in our ability to monitor such changes.

Interannual Variability of the Hydrologic Cycle over North America.[1,5,6,22] Recent research findings indicate that dominant winter modes in the hydrologic cycle are due to moisture fluxes associated with extreme precipitation events over the west coast of the United States, and are controlled by strong El Niño Southern Oscillation (ENSO) events, such as those of 1982-1983 and 1997-1998 (El Niño) and 1989 (La Niña). In the central United States, moisture transport is associated with high-precipitation events and with moisture flux variability related to the droughts of 1983 and 1988. These research results are important because they point to a moisture storage component. The results have been incorporated in a new precipitation-recycling model that includes a soil moisture storage pool. The new recycling model was used to study the variability of monthly precipitation recycling over the conterminous United States from 1979 to 2000. Specific drought or flood years do not completely account for observed variability, pointing to a storage or "memory" term response, which subsequently affects interannual precipitation variability. To explore this soil moisture control, a novel method is being developed to use energy fluxes estimated from remote-sensing platforms to show that differences in energy fluxes (which drive moisture fluxes) are related to soil moisture through deep soil layer moisture effects on surface moisture fluxes. Deep soil influences on the uptake of moisture by plant roots result in high transpiration variability and changes in the overall energy balance. This potential vegetation response to a moisture storage pool plays a crucial role in land-atmosphere interactions through water transport in the form of evapotranspiration and root uptake, and carbon transport in the form of photosynthesis and respiration. Results show explicit correlations between vegetation variability, as controlled by topography, and the ENSO and North Pacific oceanic signals. Areas of vegetation variability found to be associated with the ENSO signal are uncommon to previous studies relating precipitation and temperature to ENSO, thus indicating a novel result and pointing to the hypothesized moisture "storage" memory. The focus of the initial phase of the analysis is on the continental United States to gain insight into general, wide-ranging relationships, yet focusing on particular ecological regions with greater vegetation variability. This will give further insight into influential mechanisms linking vegetation, climate, and physiography at small scales.



Changes in the Global Water/Energy Cycle Associated with Changes in the Carbon Cycle.[10] Afforestation is the process of converting open land into forest by planting trees or their seeds. It is generally considered beneficial for carbon sequestration (at certain time scales), ecosystem protection, soil moisture retention, reducing excessive surface runoff, improving replenishment of the groundwater table, and possibly increasing local precipitation by increasing surface boundary layer moisture convergence, among other benefits. However, these benefits need to be balanced against the adverse impacts that afforestation may have in certain regions, depending on local and regional climate conditions. In this particular study, a global analysis of 504 annual catchment observations showed that afforestation dramatically decreased streamflow within a few years of planting. Across all plantation ages in the database, afforestation of grasslands, shrublands, or croplands decreased streamflow by 180 mm yr^{-1} and 38% on average. After a slight initial increase in some cases, substantial annual decreases of 155 mm and 42% were observed on average for 6- to 10-year old plantations, and average losses for 10- to 20-year-old plantations were even greater (227 mm yr^{-1} and 52% of streamflow). Perhaps most important, 13% of the studied streams dried up completely for at least 1 year, with eucalyptus more likely to dry up streams than pines. Afforestation in drier regions (<1000 mm mean annual rainfall) was more likely to eliminate stream flow completely than in wetter regions. Mean annual renewable freshwater (percentage of annual precipitation lost as runoff) decreased about 20% with afforestation. For many nations whose total annual renewable freshwater is less than 30% of precipitation, afforestation is likely to have large impacts on water resources. These results suggest that afforestation and carbon cycle issues such as carbon sequestration need to be viewed together with their interfaces with the water cycle.

Evidence for Positive Trends in Moisture Recycling at High Northern Latitudes Leading to Vegetation Increases.[3,4] Most observational indicators of global climate change have been found directly in the temperature record or in physical and ecological processes that respond to changing temperature. Researchers used a tracer approach to examine the atmospheric branch of the hydrologic cycle by following the moisture in global rainfall back to its evaporative sources over the last 25 years. Along with the first detailed analysis and climatology of the global atmospheric water cycle, their study shows evidence of trends in recycling at high northern latitudes driven by changes in circulation as well as surface temperature. These trends are consistent with observed vegetation-related changes and most evident where the density of meteorological data influencing the atmospheric analyses is high (see Figure 17).

New Land-Surface Schemes in Climate Models that Include Photosynthesis Show Improved Climate Simulations of Water-Cycle Parameters.[8] A new physiology-based model of canopy stomatal conductance and photosynthesis was included in the latest version of the Goddard Institute for Space Studies (GISS) general circulation model (GCM), Model E1. The sub-model includes responses to atmospheric humidity and CO_2 concentration, which were missing from previous GISS GCM land-surface schemes. Measurements of moisture, energy, and CO_2 fluxes over four vegetation types were used to test and calibrate the sub-model. Photosynthetic leaf nitrogen was calibrated for each vegetation type from flux measurements. The new sub-model resulted in surface cooling over many regions that were too warm in previous simulations. Some warm biases of over 2°C cooled by more than 0.5°C, including over central Eurasia, South America, the western United States, and Australia. Some regions that were previously too cool warmed, such as the Tibetan plateau. A number of precipitation biases were reduced, particularly over South America (by up to 1 mm day^{-1}) and the oceanic

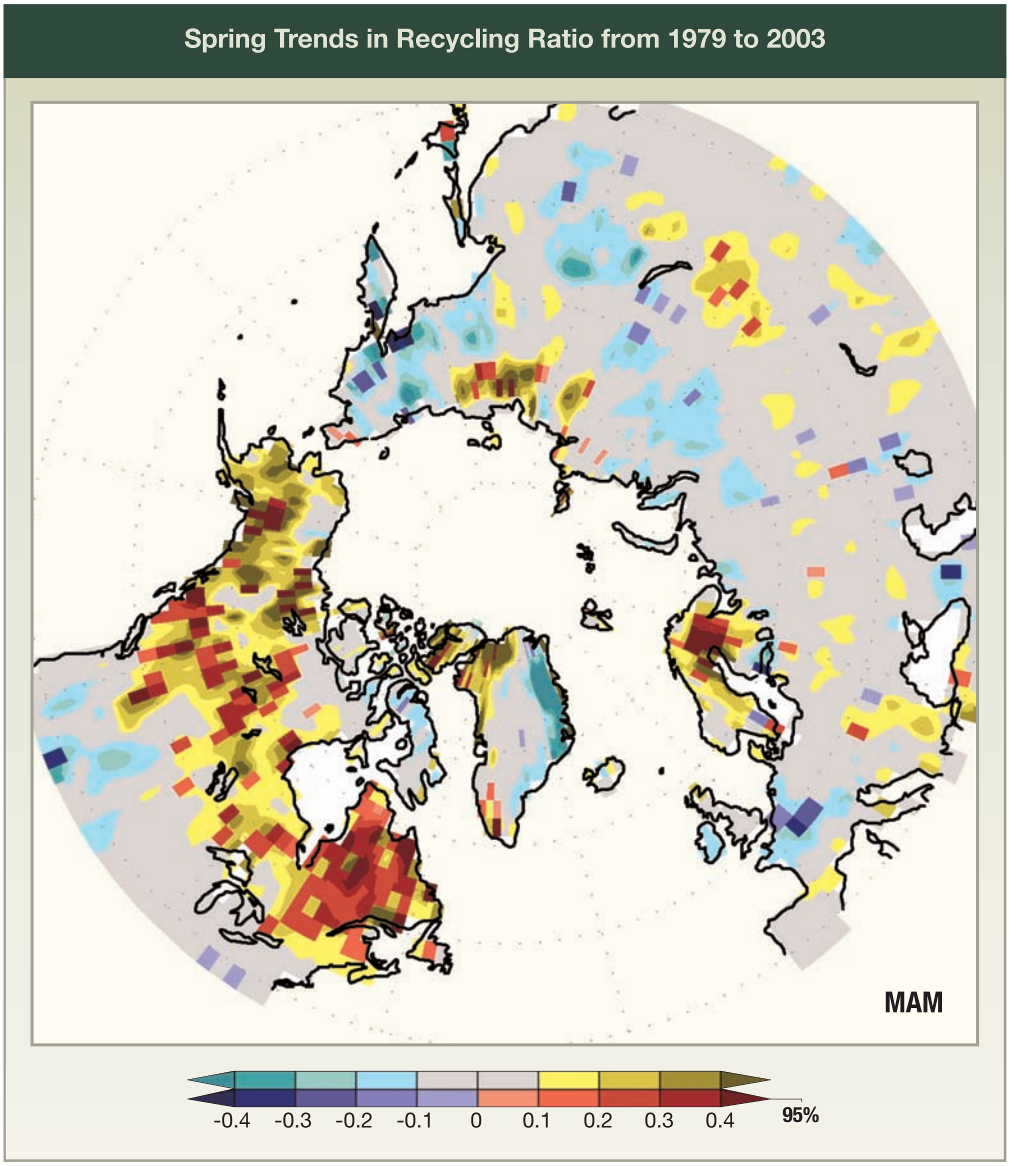


Figure 17: Spring Trends in Recycling Ratio from 1979 to 2003 over the High Latitudes of the Northern Hemisphere. Red and blue shades indicate regions of statistically significant trends with a confidence level of 95%. Positive trends dominate over North America, with especially strong and widespread trends over Canada and Alaska. There are also strong positive trends over Scandinavia during spring and over Britain and much of north-central Europe during fall (not shown here). Trends are generally weaker and not as widespread over Asia, where *in situ* meteorological observations are much less dense. *Credit: P.A. Dirmeyer and K.L. Brubaker, Center for Ocean-Land-Atmosphere Studies and the University of Maryland (reproduced from* **Geophysical Research Letters** *with permission from the American Geophysical Union).*

inter-tropical convergence zone (by ± 1 mm day^{-1}), while coastal West Africa became significantly wetter. Cloud cover increased over many land areas previously too clear. Higher absolute canopy conductances and positive feedbacks with atmospheric humidity were largely responsible for the simulated vegetation influence on the atmosphere. High-latitude climate changes through the remote effects of increased tropical latent heating (heat released by precipitating clouds) resulted directly from improved characterization of tropical forest canopy conductance. The realistic representation of stomatal control of land evaporation and evapotranspiration is critical for the accurate simulation of atmospheric dynamics in climate models. Figure 18 shows seasonal maps of mean precipitation bias.

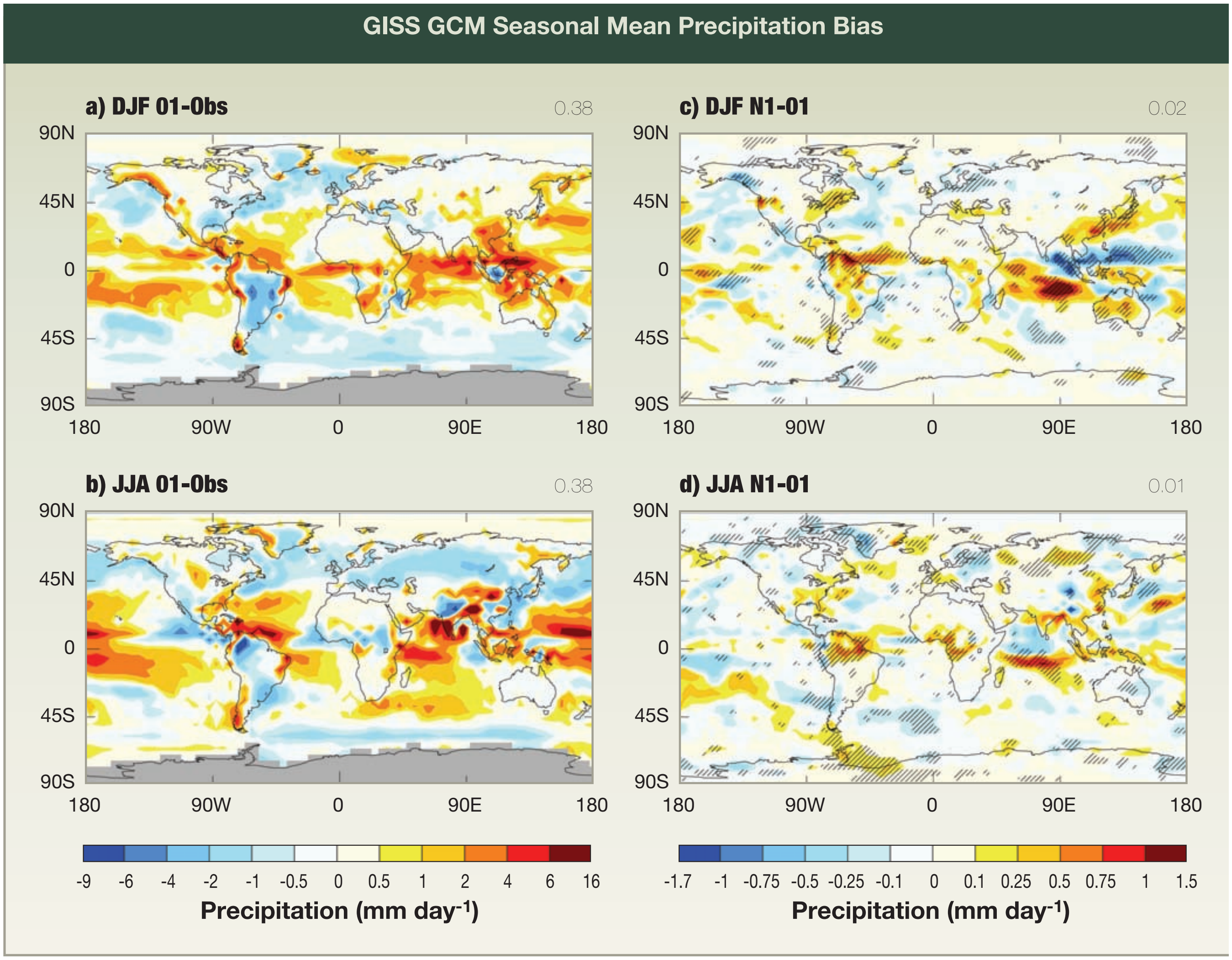
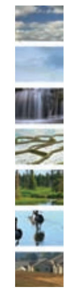


Figure 18: GISS GCM Seasonal Mean Precipitation Bias. These products generated using the RA97 canopy stomatal conductance sub-model in (a) DJF (-7.1 to +9.3 mm day^{-1}) and (b) JJA (-8.7 to +15.9 mm day^{-1}), and change due to new conductance sub-model in (c) DJF (-1.4 to +1.5 mm day^{-1}) and (d) JJA (-1.7 to +1.1 mm day^{-1}). Observations over land from New *et al*. (1999) and over oceans from Huffman and Bolvin (2005). Global means at upper-right corners. Hatched areas are significant at the 95% confidence level for a paired *t* test. *Credit: A.D. Friend, Laboratoire des Sciences du Climat et de l'Environnement; and and N.Y. Kiang, Columbia University (reproduced from* **Journal of Climate** *with permission from the American Meteorological Society).*

Correspondence between Observations and Streamflow Simulations by Climate Models, and Future Streamflow Projections.[16] CCSP scientists analyzed the long-term streamflow characteristics in an ensemble of recent climate simulations and projections by 12 different global climate models. They found encouraging correspondences between observed historical and simulated patterns of 20th-century regional streamflow variations on multi-decadal time scales. The same models project 10 to 40% increases in runoff in eastern equatorial Africa, the La Plata basin, and high-latitude America and Eurasia, and 10 to 30% decreases in southern

Africa, southern Europe, the Middle East, and mid-latitude western North America by 2050 under a mid-range scenario of greenhouse gas emissions leading to an atmospheric CO_2 concentration of approximately 530 ppm by the mid-21st-century.



Linking the Time Scales and Amplitudes of Groundwater and Surface Water Flows to Global Climate Variations.[9] The time scales and amplitude of the hydrologic responses to climate variations depend on the time scales and mechanisms of the climate forcings, on how closely the groundwater and surface water systems are coupled to each other and to climate variations, and whether the overall hydrologic responses in a given setting depend more on slower aquifer responses or more rapid streamflow responses. An innovative study used a global GCM (ECHAM-T42) coupled to a regional groundwater model (RGWM) of the Santa Clara-Calleguas Basin to examine the simulated precipitation rates from the GCM for the period 1950 to 1993. The study found that interannual to interdecadal time scales of ENSO and Pacific Decadal Oscillation climate variations are imparted to the simulated climate-driven recharge (and discharge) variations. For example, the simulated response of average groundwater level to ENSO variations at a key observation well in the basin is 1.2 m per °C compared to 0.9 m per °C in the observations. This close agreement shows that the GCM-RGWM combination can translate global-scale climate variations into realistic groundwater responses. Figure 19 illustrates the spatial relationships and groundwater budgets of components of the water resource extraction and distribution systems for the Santa Clara-Calleguas Basin.

The Groundwater Connection in the Amplification of Seasonal- to Century-scale Oscillations in Closed Basins.[7,20] A recent study shows that the space-time components of runoff have a complex relationship with orography, where the balance of precipitation and evapotranspiration interacts with the mountain-front watershed to filter and amplify runoff to the Great Salt Lake. The study examined the space-time patterns of annual, interannual, and decadal components of precipitation, temperature, and runoff using long-record time series across the steep topographic gradient of the Wasatch Front in northern Utah. This region forms the

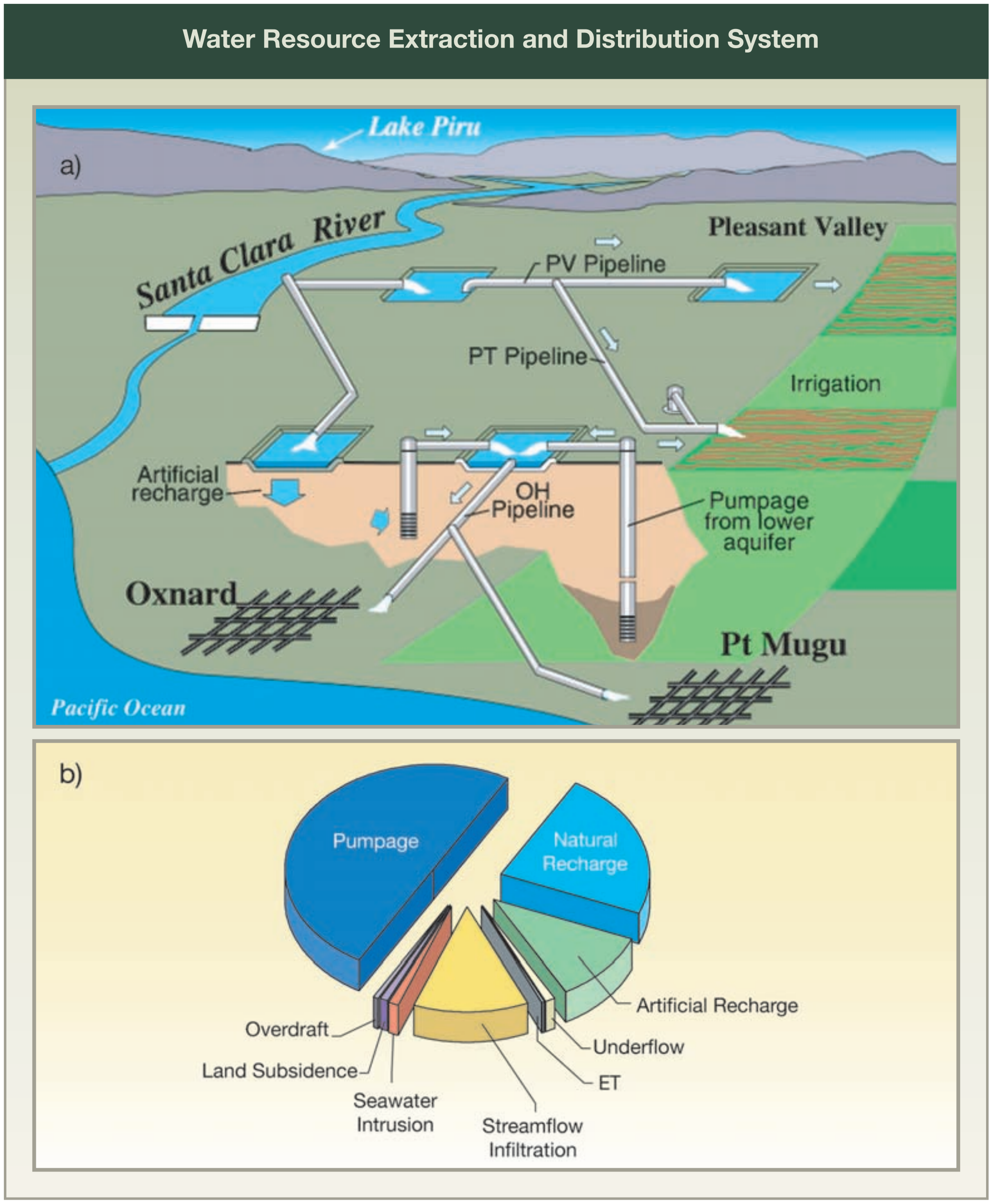


Figure 19: Water Resource Extraction and Distribution System. (a) Diagram showing components of water resource extraction and distribution system; and (b) generalized groundwater budget for the Santa Clara-Calleguas Basin, Ventura County, California. *Credit: R.T. Hanson and M.D. Dettinger, University of California at San Diego.*

major drainage area to the Great Salt Lake. The approach used multi-channel singular spectrum analysis as a means of detecting dominant oscillations and spatial patterns in the data (see Figure 20 for a depiction of the spatial patterns). Results showed that high-elevation runoff is dominated by the annual and seasonal harmonics, while low-elevation runoff exhibits strong interannual to decadal oscillations. In particular, significant low-frequency components are found at intermediate and low elevations of the Wasatch Range. The research suggests that these results are due to mountain-front hydrologic conditions supporting groundwater storage and base flow. The transmission

Wetting and Drying Phases of the Great Salt Lake

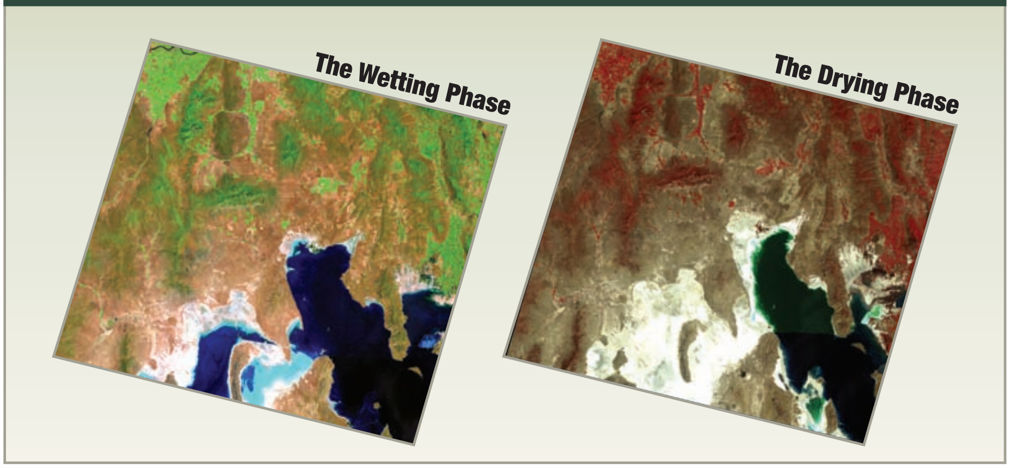
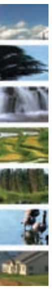


Figure 20: Wetting and Drying Phases of the Great Salt Lake. *Credit: C. Duffy, Pennsylvania State University and USGS for the original Landsat imagery.*

zone, or the zone of streamflow loss to groundwater, was identified as affecting annual, interannual, and decadal runoff components. Overall, the groundwater-streamflow relation represents a "low-pass" filter for the precipitation/evaporation input signal. The filtering effect is likely to be proportional to the scale of volumetric groundwater storage in the mountain blocks and basin sediments.

Collaborative Research: Development of Informatics Infrastructure for Hydrologic Sciences.[14] Scientists associated with the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc. (CUAHSI) have developed a Hydrologic Information System (HIS) that combines point data (on-site measurements), spatial data (GIS-based geographical data), remotely sensed (satellite) data, and meteorological data. HIS provides a "digital watershed" with access through a common portal to a wide variety of hydrologic and water quality data collected by many agencies, and with a "translator" that makes seamless connections. HIS will later be expanded to provide hydrologic representations and analyses. With this hydrologic digital library, users can find desired items through web-based searches and acquire them through automated data acquisition systems. The goal is to allow the scientific community and resource managers to access information needed to define fluxes and flow paths, residence times, and mass balances—key elements for testing hydrologic hypotheses. HIS provides data fusion for mating and communication among different formats to form a coherent framework in space and time.



HIGHLIGHTS OF PLANS FOR FY 2007

Priorities of the CCSP global water cycle research element include continuing U.S. and global observations, field campaigns, and experiments; improvements to data integration and analysis systems; diagnostic and predictive model development; and applications to decision-support systems. A fundamental objective of the program is to ensure that observational capability is enhanced and improved, and that the data assimilation and modeling/prediction systems are more reliable and accurate at the point of application. Several promising results from recent research will be further explored with an aim to transfer this knowledge to operational applications that provide societal benefit. Concurrently, a cohesive research strategy will be implemented to improve the current deficiencies in understanding that exist regarding many aspects of the regional and global water cycle. Several scientific questions remain, ranging from warnings of natural hazards to the impact of global climate change, be it from natural or anthropogenic causes. The program outlined for FY 2007 will lead to improvements in planning, decisionmaking, and resource management activities—a major aim of the program. However, significant unresolved research issues will require longer term efforts. To address these research and applications needs, several initiatives will be launched in FY 2007. Following are selected highlights of FY 2007 activities.

Integration of Water Cycle Observations, Research, and Modeling: A Prototype Project. Following CCSP guidelines, an interagency "integrating" priority project will be implemented (contingent on funds) as the first of similar activities that are envisaged under the water cycle element over the next decade. The purpose of this project is to address significant uncertainties associated with the water cycle through a study that comprehensively addresses the water budget within a limited spatial and temporal domain. This FY 2007 prototype project will integrate information describing the state, fluxes, and variability associated with and across hydrologic regimes. To accomplish this FY 2007 near-term priority, a number of agencies are planning to contribute to DOE's planned field campaign (CLASIC) at the ARM Southern Great Plains site. The multi-agency effort will include space-based observations, aircraft campaigns, surface and subsurface hydrologic components, isotopic measurements, CO_2 fluxes, research-mode modeling, and applications to decision-support systems as a first integrated, interagency attempt to build the science and applications components required to begin to "close" the water budget within a limited area.

This activity will address CCSP Goals 1, 2, 3, and 5
and Questions 5.1, 5.2, 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

Participation in the Convective and Orographically Induced Precipitation Study. The ARM Mobile Facility (AMF) will participate in the international Convective and Orographically Induced Precipitation Study in the Black Forest area in summer 2007. The goal is to identify the reasons for deficiencies in the quantitative precipitation forecast and to improve the skill of mesoscale model forecasts with respect to precipitation. 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 AMF to study cloud and radiation processes in multiple climatic regimes. The AMF can be deployed to sites around the world for durations of 6 to 18 months. Data streams produced will be available to the atmospheric community for use in testing and improving parameterizations in global climate models.

This activity will address CCSP Goals 1, 2, and 3
and Questions 5.1, 5.2, and 5.3 of the CCSP Strategic Plan.

The Cloud and Land Surface Interaction Campaign. The Cloud and Land Surface Interaction Campaign (CLASIC), a field campaign proposed by DOE for implementation in FY 2007, will focus on interactions between the land surface and the early cumulus life cycle, especially the stages leading from cumulus humilis to cumulus congestus. It will cover a period of 1 to 3 months and will straddle the winter wheat harvest when large changes in the land surface lead to large changes in surface albedo, latent heat flux, and sensible heat flux. By DOE's invitation, CLASIC will be developed further as an integrated, interagency project, contingent on FY 2007 funding and on expressions of multi-agency interest (see next item).

This activity will address CCSP Goals 1, 2, 3, 4, and 5
and Questions 5.1, 5.2, and 5.3 of the CCSP Strategic Plan.

Blueprint for an Integrated Observing Platform: Bedrock to Boundary Layer and Beyond. The Science Steering Group (SSG) for the CCSP water cycle element will develop a blueprint for a hypothetical integrated observing platform that would be capable of quantifying all aspects of the terrestrial water and energy cycle. The plan will be conceptual but with sufficient specific detail so that one or more aspects of the platform could be implemented during one or more of the integrated

interagency projects that the water cycle element may carry out over the next decade of research and applications. The blueprint could also serve as a basis for deploying terrestrial hydrologic observatories, and be used for the planning of field campaigns. The conceptual plan will include observational requirements that derive from needs for improved models of the water cycle, improved water cycle process parameterization schemes, scale interactions, and improved characterization and modeling of fluxes and transports in the atmosphere, land surface (including vegetation, streams, and reservoirs), subsurface (including the water table and subterranean aquifers), and coastal zones. The inclusion of remote-sensing and *in situ* instruments, fixed and portable, are envisaged. Existing observing systems will form the substrate for the integrated observing platform to which innovative technological capabilities and designs will be added. The plan will make the case for the need for new and improved observational and modeling capability to address known scientific challenges facing both water cycle research and applications to the management of water resources (quantity and quality).

This activity will address CCSP Goals 1, 2, 3, 4, and 5 and Questions 5.1, 5.2, and 5.3 of the CCSP Strategic Plan.

Integration of Space-Based Observations and Land Surface/Hydrology Data Assimilation Systems. The GRACE satellite has demonstrated that large-scale changes in the integrated column water content of the combined atmosphere, land surface (including rivers and reservoirs), soil moisture, and groundwater system compares well with the changes documented by the Global Land Data Assimilation System. Investigations in FY 2007 will further explore whether GRACE data can be assimilated by and/or provide integral closure constraints for the Land Information System (LIS) to improve the water/energy cycle research and applications analysis products generated by these systems. This will be done alongside data assimilation work to incorporate other satellite data products (e.g., soil moisture, snow cover area and water equivalent, and surface temperature) into LIS.

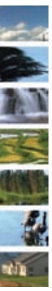
This activity will address CCSP Goals 1, 2, and 3 and Questions 5.1, 5.2, 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

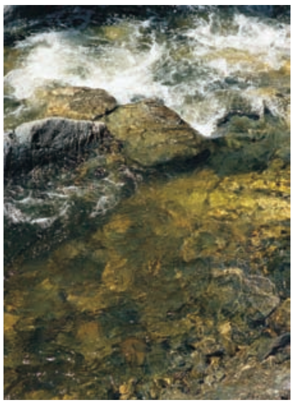
Advanced Ensemble Multi-Model Prediction Techniques for Surface and Subsurface Hydrologic Parameters. Expanded efforts will be made to calibrate and validate research-mode ensemble (multi-model) forecasting techniques for surface and subsurface hydrologic parameters, especially at longer seasonal time scales. The objective is to transfer the improved hydrologic prediction techniques to operational applications at seasonal and interannual time scales. This activity will expand on the recently developed Advanced Hydrological Prediction Service (AHPS) of NOAA's hydrologic forecasting system that includes new model calibration strategies, distributed modeling approaches, ensemble forecasting, data assimilation techniques, enhanced data analysis procedures, flood forecast inundation maps, hydrologic routing models, and multi-sensor precipitation estimates. Data from USGS stream flow observations and gridded multi-sensor precipitation and snow-water equivalent estimates, among other data, will also be transferred into the AHPS data assimilation system. New approaches for remotely sensing precipitation, snow, and other inputs will be integrated into the hydrologic forecast operation. AHPS is slated to be fully implemented nationwide in 2013. In parallel, CCSP researchers will participate in the further development of an international project, the Hydrological Ensemble Prediction Experiment. This project will bring the international hydrological community together with the meteorological community and demonstrate how to produce reliable hydrologic ensemble forecasts that the emergency management and water resources sectors can use with confidence to make decisions that have important consequences for the economy and for public health and safety.

This activity will address CCSP Goals 1, 3, 4, and 5
and Questions 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

A New Strategy for Improving Water/Energy Cycle Components in Earth/Climate System Models. Integrated Earth/climate system modeling efforts, combining the water/energy cycle and other components of the climate system, will be actively pursued in FY 2007 and beyond. In particular, recent observations, diagnostic studies, and research analyses have demonstrated the need to incorporate certain elements in weather forecast and climate (variability) prediction models operating at various time scales. For short-term forecasting (e.g., 5 to 10 days), these elements include the diurnal cycle, coupling between the atmosphere and the ocean (mixed layer down to the thermocline at a minimum), and the coupling of the land surface (including vegetation) and subsurface hydrology (down to the water table at a minimum) to the atmosphere. For climate variability predictions (e.g., monthly to seasonal and beyond), these elements include the dynamics of the interaction between the ocean mixed layer and the deeper mid-ocean, the dynamics of interactions between the land and the water table, and dynamic vegetation changes. These components have a direct impact on the interaction and exchange fluxes of water, energy, heat, and momentum at the interfaces between the atmosphere and the land surface/vegetation or the oceans. For longer climate change time scales, fully coupled models of the atmosphere-land and hydrosphere/biosphere-ocean-cryosphere are required. The key issue is how to observe and model coupling processes. To support this activity, improved observing systems are also required. This effort is considered central to CCSP, and the global water cycle element plans to pursue this activity jointly with other CCSP program elements. This integrating activity will be initiated in FY 2007, but implementation is expected to take the better part of a decade for improvements in the system of combined observations, modeling, prediction, and applications.

This activity will address CCSP Goals 1, 2, 3, 4, and 5 and Questions 5.1, 5.2, 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.





Science Plans for the Extension of the Global Energy and Water Experiment (GEWEX)-Coordinated Enhanced Observing Period (CEOP) through 2010. The initial successes of CEOP have led its Science Steering Committee and its Advisory and Oversight Committee to endorse plans for a second phase of CEOP that will extend to the end of 2010. This decision, which CCSP global water cycle scientists are closely involved with, has also been supported by the broader World Climate Research Programme (WCRP) community. The WCRP Joint Scientific Committee (JSC) has taken steps to help develop the unique attributes of CEOP's observation and data component by providing guidance through the WCRP Observations and Assimilation Panel. In a similar manner, the JSC plans to ensure that the CEOP science focus remains closely integrated with and complementary to the overall objectives of GEWEX and the other core projects of WCRP. In this manner, CEOP will continue to evolve as a leading contributor to water and energy cycle studies in the global climate research community and remain a fully functioning integrative component of the WCRP. CCSP researchers will contribute to CEOP in developing the Phase 2 Implementation/Science Plan.

This activity will address CCSP Goals 1, 2, and 3 and Questions 5.1, 5.2, and 5.3 of the CCSP Strategic Plan.

New Watershed Climate Assessment Decision-Support Capabilities. Climate change presents a range of risks and opportunities to water managers. To minimize risk and take advantage of opportunities, tools are necessary to promote adaptive and forward-looking environmental management by decisionmakers at all levels. Several projects have been initiated in the area of decision support. A new climate assessment capability, the Better Assessment Science Integrating Point and Non-point Sources (BASINS) watershed modeling system, is being developed. BASINS combines data and models from agencies including EPA, USDA, and USGS in a single system. The new tool will facilitate assessment of the influence of climate variability and change—together with land-use change and other stressors—on water quantity and quality. The tool will also provide the capacity to evaluate potential adaptation strategies to increase the resilience of water systems to changes in climate.

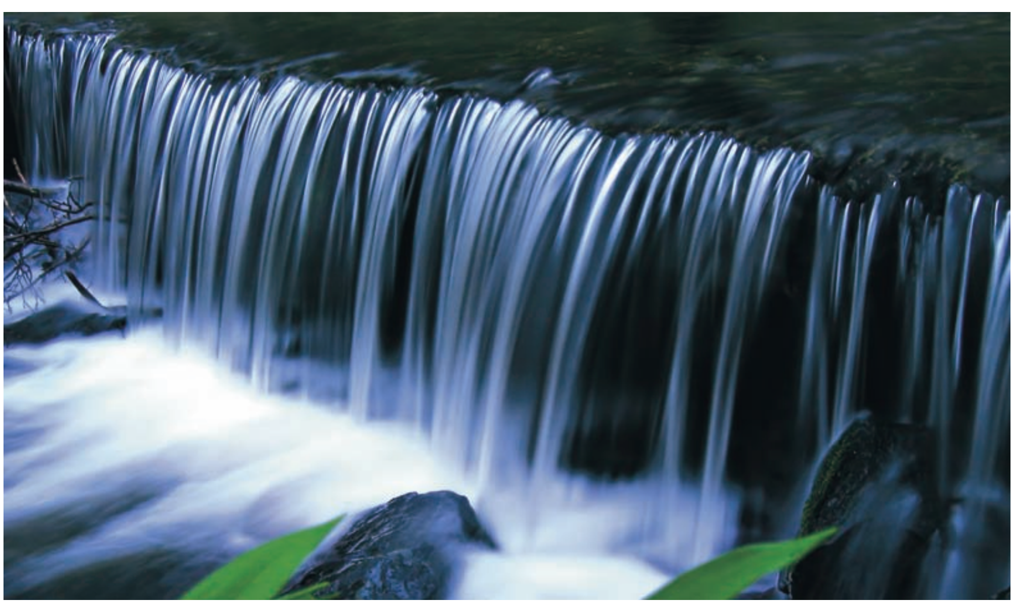
This activity will address CCSP Goals 4 and 5 and Questions 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

New Tools for the Assimilation of Remote-Sensing Data into Distributed Water Quality and Sediment Transport and Erosion Models. The research activities of the USDA Agricultural Research Service (ARS) in the area of land data assimilation systems and model analysis are focused on the efficient integration of ground-based and remote-sensing data into critical resource and conservation practice assessment models. Existing agency research projects are aimed at the sequential assimilation of surface soil moisture retrievals and vegetation indices from microwave and visible remote sensors to constrain crop growth and root-zone water balance models. Future work will expand this emphasis to include the assimilation of remote-sensing data into distributed water quality and sediment transport and erosion models. Particular emphasis will be paid to developing data assimilation and modeling capabilities to quantify benefits arising from the adoption of conservation practices within agricultural watersheds.

This activity will address CCSP Goals 4 and 5
and Questions 5.4 and 5.5 of the CCSP Strategic Plan.

Tools to Help Develop "Best Management Practices" to Lessen the Impacts of Climate Variability and Change. Similar to BASINS, a decision-support capability is being developed with models from EPA and the ARS Water Erosion Prediction Project soil erosion model. The new climate assessment capability will enable land managers to develop best management practices to lessen the impacts of climate variability and change on sediment loading to streams.

This activity will address CCSP Goals 4 and 5
and Questions 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

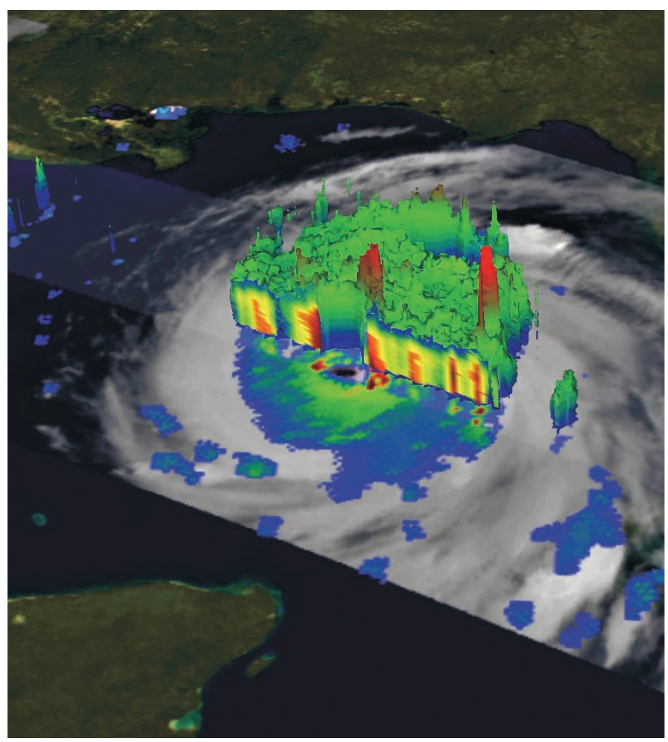


Integration of Information on the Effects of Changing Precipitation Patterns into Infrastructure Planning Processes. Communities around the United States are investing billions of dollars on upgrading combined sewer systems to comply with new regulations for combined sewer overflows. Previous work has suggested that climate change could alter the effectiveness of existing long-term control plans. Work has been initiated with local utility managers to better integrate information on the effects of changing precipitation patterns into infrastructure planning processes using decision-support tools such as those models developed by EPA in collaboration with other agencies.

This activity will address CCSP Goals 4 and 5 and Questions 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

Initial Analysis and Calibration/Validation of Observations from the CloudSat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) Research Satellites. Researchers plan to use new observations from CloudSat and CALIPSO, launched in mid-FY 2006, to measure the vertical structure of clouds and aerosols and to improve understanding of their radiative properties. The data will also provide vital information on global and regional pollution transport and its direct and indirect effects on cloud and precipitation processes, of which the latter are much more difficult to quantify. The data will complement existing satellite observations from Terra, Aqua, Aura, and Tropical Rainfall Measuring Mission (TRMM) as well as surface-based observations from ARM and the Baseline Surface Radiation Network, among others. As possible, and contingent on FY 2007 funding, these data will be utilized, in research mode, in the interagency integrated field campaign proposed as an interagency expansion of CLASIC.

This activity will address CCSP Goals 1, 2, and 3 and Questions 5.1, 5.2, and 5.3 of the CCSP Strategic Plan.



Combined Management of Groundwater and Surface Water Resources. Recent experimental research shows that coupling global GCMs with regional groundwater and surface water models have predictive capabilities that exceed the capabilities of the individual component models, especially at time scales that are important to water resource management. These early research findings will be tested further with the objectives of improving the combined water resources prediction system and transferring these research results into information that supports the operational decisionmaking infrastructure and decision-support systems. This new concept will be integrated into the implementation strategy of the global water cycle component over the next decade. Early testing will be attempted during one or more of the interagency integrated projects currently being planned for the next several years of the program. Further calibration will also allow for improved assessments of the impacts of projected global climate change at regional and local spatial scales.

This activity will address CCSP Goals 1, 2, 3, 4, and 5 and Questions 5.1, 5.2, 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

Research on Extended Drought: Causes, Monitoring, Analysis, Prediction, and Support for Drought Information Systems. Extended droughts have large impacts on water resources, agriculture, the energy industry, and natural ecosystems, among others. The global water cycle element places considerable importance on research into the causes of extended droughts and their prediction or early warning through several, if not all, of the activities identified previously. The activities include the need for better observing and monitoring systems (surface- and space-based), cloud and precipitation process studies, improved coupled modeling and prediction systems, and integrated data and information delivery systems. Major scientific issues also need to be resolved regarding the response of the continental water cycle to projected global warming, including how soil moisture balance will affect evaporation

in response to greater energy availability at the land surface; how warming will influence the partitioning of water at the land surface between surface runoff and groundwater recharge; and how likely vegetation is to respond to changes in the timing and rates of water and energy supplies to the atmosphere-land surface interface. This new activity is aimed specifically at a better understanding and prediction of droughts and the processes that cause them, which cut across many temporal and spatial scales ranging from seasonal to interannual to decadal, and from regional to continental. Moreover, as a renewed effort in FY 2007 and beyond, plans are being developed to incorporate enhanced information throughflow from research to experimental analysis and prediction systems to applications that supply the data needed by planning and decisionmaking infrastructures. This activity will be carried out jointly with other CCSP interagency working groups such as Climate Variability and Change, Land-Use and Land-Cover Change, Ecosystems, Carbon Cycle and particularly Decision Support and Human Contributions and Responses, thereby contributing to the recently established National Integrated Drought Information System.

This activity will address CCSP Goals 1, 4, and 5
and Questions 5.4 and 5.5 of the CCSP Strategic Plan.

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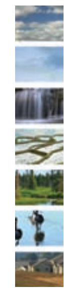
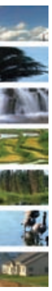




4 | Land-Use and Land-Cover Change

Strategic Research Questions

6.1 What tools or methods are needed to better characterize historic and current land-use and land-cover attributes and dynamics?

6.2 What are the primary drivers of land-use and land-cover change?

6.3 What will land-use and land-cover patterns and characteristics be 5 to 50 years into the future?

6.4 How do climate variability and change affect land use and land cover, and what are the potential feedbacks of changes in land use and land cover to climate?

6.5 What are the environmental, social, economic, and human health consequences of current and potential land-use and land-cover change over the next 5 to 50 years?

See Chapter 6 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of these research questions.

Land-cover and land-use change affect the global climate system directly through biogeochemical and biogeophysical processes. Biogeochemical processes of land-cover and land-use change affect global climate by changing the chemical composition of the atmosphere. Deforestation, for example, is a major source of atmospheric CO_2 resulting from the oxidation and decomposition of tree biomass, because the vegetation that replaces forests frequently contains less carbon than the forests they replace. Biogeophysical processes of land-cover and land-use change affect the absorption and disposition of energy at the Earth's surface. The albedo (reflectivity) of the Earth's surface determines how much of the Sun's energy is absorbed, hence available at the surface in the form of heat. Vegetation transpiration and surface hydrology determine how the energy received at the surface of the Earth is partitioned into latent and sensible heat fluxes. Vegetation structure determines surface roughness, which in turn is directly related to momentum and heat transport.

A global modeling study has shown that the effects of projected changes in land cover lead to significantly different regional climatic conditions in 2100 as compared with climatic conditions resulting from atmospheric greenhouse gas forcings alone. For example, agricultural expansion produced significant additional warming over the Amazon Basin and a cooling of the upper air column and nearby oceans, as well as cooling and decreases in the mean daily temperature range over many mid-latitude areas. In another regional study, a CCSP collaborative research project used numerical modeling to evaluate the impact of anthropogenic land-cover change on the regional climate of south Florida. Simulations of regional climate using the Regional Atmospheric Modeling System compared climate patterns under modern and pre-development land cover reconstructed from paleoecological and historical records. Spatial patterns of surface sensible and latent heat flux differed significantly under the different land-cover schemes, and model results indicate that land-cover changes increased summertime maximum temperatures and decreased warm season convective rainfall by 10 to 12%. Refer to chapter references 4, 6, and 7 for detail regarding these illustrative findings.

HIGHLIGHTS OF RECENT RESEARCH

Global Geographically Registered Landsat Data Set.[11] Earth's land surface is spatially variable at scales of meters to tens of meters, due to local terrain variability and associated microclimatic influences on vegetation types and associations. Accordingly, spatial data at the scale of tens of meters are required to accurately map many areas, because of the low spatial autocorrelation of land-surface features. In addition, a variety of natural and human land-use changes (e.g., wildfires, deforestation, wetland conversion, and urbanization) represent alterations of landscapes, which also occur at spatial scales of tens of meters. These are important perturbations of the global environment and require similar spatial-scale data for quantification. Information is currently lacking about where environmental change is occurring, what the changes are, and what the post-change properties of the altered areas are. Landsat data are available at these spatial scales and are consequently extremely useful for studying land-use and land-cover change from space.

A global land data set having high spatial accuracy has been developed using Landsat Multi-Spectral Scanner, Thematic Mapper, and Enhanced Thematic Mapper data from the 1970s, circa 1990, and circa 2000, respectively, to support a variety of scientific studies and educational purposes. This is the first time a geodetically accurate global compendium of multi-epoch digital satellite data at the 30- to 80-m spatial scale spanning 30 years has been produced for use by the international scientific and educational communities. These data are being distributed from multiple locations and are currently being used for land-use and land-cover change research (see Figure 21).

Landsat Mosaic over the Southern Portions of Lake Michigan

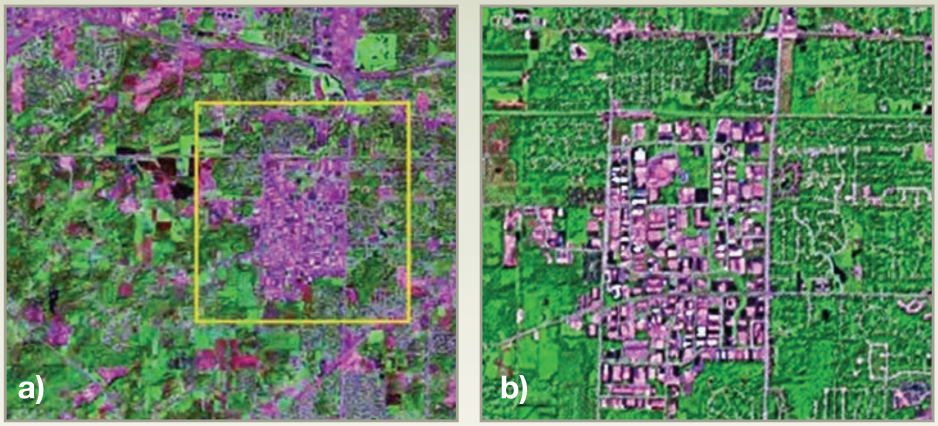


Figure 21: Landsat Mosaic over the Southern Portions of Lake Michigan. Landsat mosaic products over the southern portions of Lake Michigan and adjacent areas of the United States: (a) a full-resolution 28.5-m^2 subset for the circa 1990 epoch; and (b) a full-resolution 14.25-m^2 subset of the circa 2000 epoch. These are examples of the data available globally from NASA's Global Ortho-Rectified Landsat Data Set. *Credit: C.J. Tucker, NASA/ Goddard Space Flight Center.*

Understanding environmental or land-cover dynamics represents an important challenge in the study of the global environment, since many land-cover changes take place at fine scales of resolution, requiring Landsat-type imagery for accurate measurement. Uses for such data range from biodiversity and habitat mapping for localized areas to specifying parameters for large-scale numerical models simulating biogeochemical cycling, hydrologic processes, and ecosystem functioning. Recent work has stressed the importance of the effects of land-cover change on climate.

Landsat Ecosystem Disturbance Adaptive Processing System: A North American Forest Disturbance Record from Landsat.[8] Forest-cover conversion, disturbance regimes, and recovery from conversion and disturbance have been proposed as primary mechanisms for transferring carbon between the land surface and the atmosphere, but the area and timing of these processes is still poorly quantified. A pilot project, the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) has been initiated to "mine" the Landsat observational record, which spans more than 33 years, in order to assess forest disturbance across all of North America, in support of the CCSP's North American Carbon Program. Figure 22 shows an example of the products from this project.

Landsat Thematic Mapper and Enhanced Thematic Mapper data have been corrected for atmospheric obscuration using algorithms and processing approaches derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the Terra and Aqua satellites. To date, some 2,200 Landsat images covering North America have been corrected, and can be downloaded from the LEDAPS web site, <ledaps.nascom.nasa.gov/ledaps/ledaps_NorthAmerica.html>. Disturbance and recovery are being mapped using a multi-spectral "Disturbance Index" algorithm. By late-2006, scientists will be able to download maps of forest change for the interval 1990 to 2000, both at full resolution (30 m) and coarse resolution suitable for carbon modeling (500 m and 0.05 degree). Later releases will cover the period 1975 to 1990. Funded by NASA, the LEDAPS project includes researchers from NASA, the U.S. Forest Service, and the University of Maryland.

LEDAPS Forest Disturbance Mapping

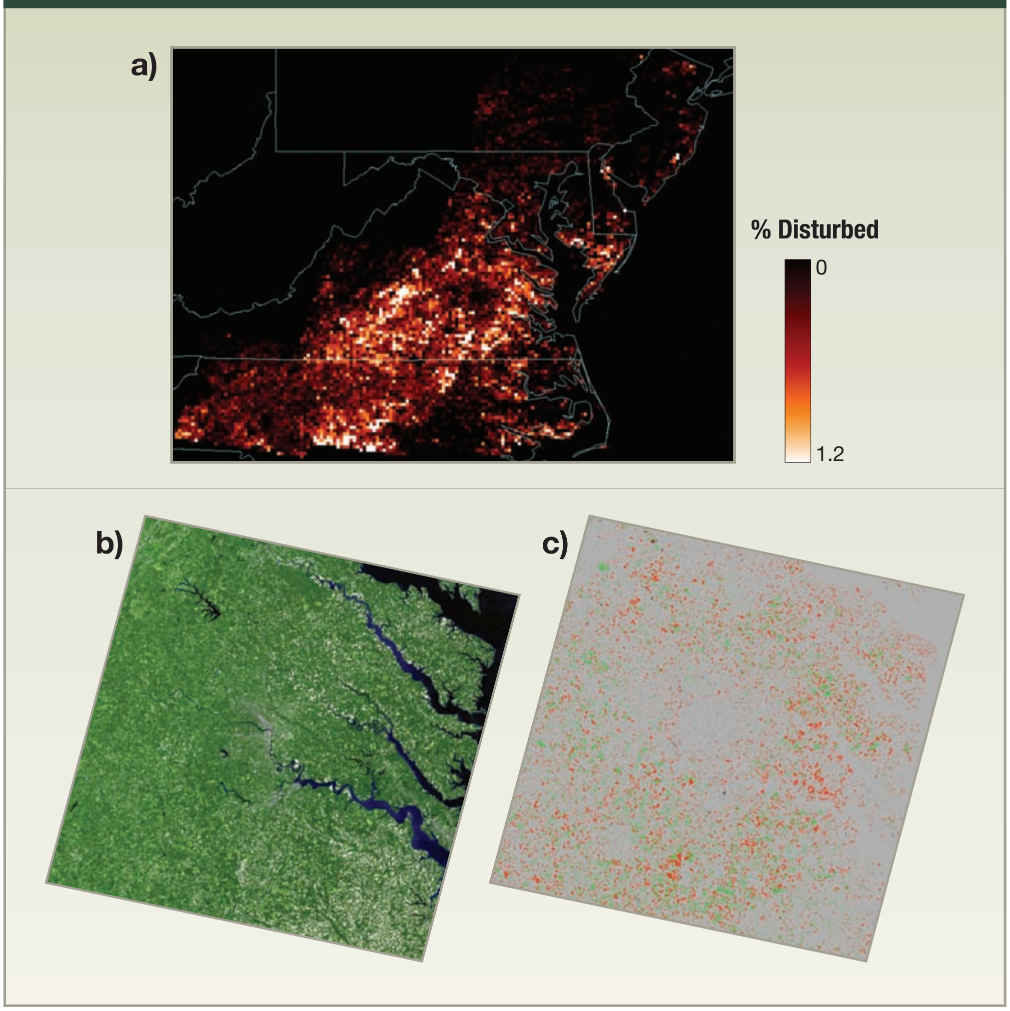


Figure 22: LEDAPS Forest Disturbance Mapping. These products provide examples of LEDAPS forest disturbance mapping: (a) 0.05° modeling grid showing the percent of each cell area disturbed (harvested) per year for the mid-Atlantic from 1990 to 2000; (b) atmospherically corrected Landsat surface reflectance image for the Richmond, Virginia, region; and (c) high-resolution map of forest disturbance (red) and regrowth (green) for the Richmond region, 1990 to 2000. *Credit: J.G. Masek, E.F. Vermote, N.E. Saleous, R. Wolfe, F.G. Hall, K. Huemmrich, F. Gao, J. Kutler, and T.K. Lim, NASA/Goddard Space Flight Center and the University of Maryland (reproduced from* **Geoscience and Remote Sensing Letters** *with permission from the Institute of Electrical and Electronics Engineers ©2006).*

Mapping 50 Years of Forest Conversion in Madagascar with Satellite Data. The Ortho-rectified Landsat Global Data were used to quantitatively determine the tropical moist forest, tropical deciduous forest, and spiny woodland of Madagascar for the 1970s, 1990, and 2000. The satellite data were analyzed and field verifications were performed by low-altitude aerial reconnaissance, errors in the analysis were corrected, and a more accurate classification for the entire island (590,000 km^2) produced. The satellite data were combined with aerial photographs to extend the work back to the 1950s.

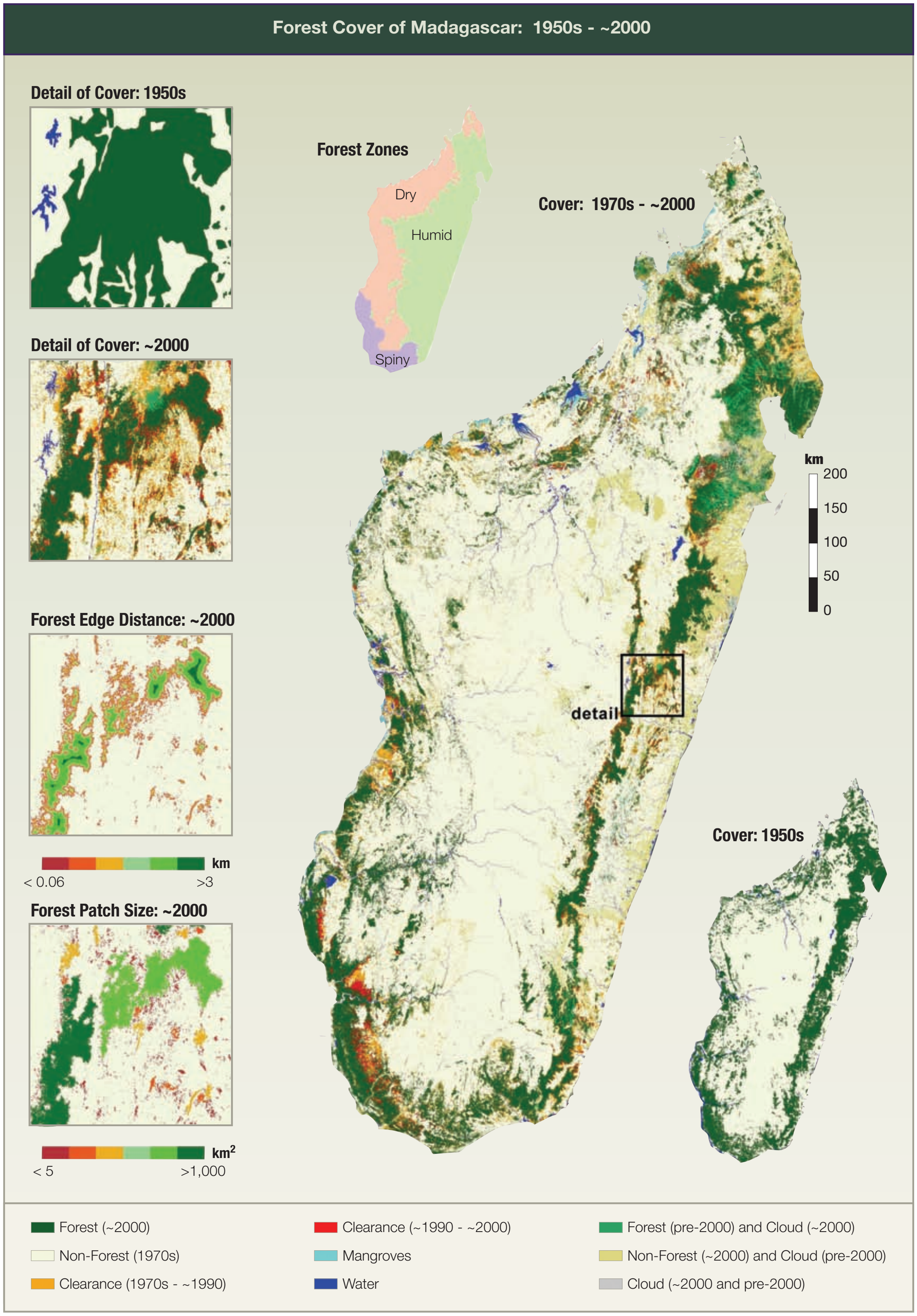
Madagascar's forest cover decreased substantially over the 50-year period, from 27% of the island in the 1950s to only 16% circa 2000 (see Figure 23). Taking the fragmentation of forests into consideration, the decrease was even more drastic. From the 1950s to circa 2000, the area of "high-quality," or interior forest more than 1 km from a non-forest edge, decreased from 90,000 km^2 to less than 20,000 km^2, and the area in patches of greater than 100 km^2 decreased by more than half. Deforestation rates slowed in the 1990s for the tropical humid and dry forests, but not for the spiny forest. However, the clearing rates are still of concern among all forest types, considering the small portion of remaining habitat.

The results emphasize the need for more effective forest conservation in Madagascar. The researchers suggest goals of halting further primary forest clearance as soon as possible, and initiating strategically located forest restoration efforts. Given the lag time of species extinction after habitat destruction, it is probable that many species are living on borrowed time; forest restoration could partially mitigate this dynamic.

Land Cover, Land-Use Change, Human Dimensions, and Wildlife Conservation in Ngorongoro Conservation Area, Tanzania.[1] The Ngorongoro Conservation Area in Tanzania has a dense population of African wildlife that coexists with an expanding human population of Maasai agro-pastoralists and non-Maasai agriculturalists. The expanding human population has started to encroach upon the savanna areas that the wildlife and the domestic animals of the Maasai agro-pastoralists use in common. To complicate matters further, the savanna areas within the Ngorongoro Conservation Area are climatically variable and strongly influenced by El Niño and La Niña events: droughts are experienced under El Niño conditions and excessive rain occurs under La Niña conditions.

Landsat satellite data were used to map the conversion of pastoral areas to cultivation. By 2000, cultivation had increased to 40 km^2 of the 8,300-km^2

Figure 23: Forest Cover of Madagascar, 1950s to ~2000. Forest cover changes from the 1970s to circa 2000 are shown in the main figure. Forest cover in the 1950s is shown in the lower right inset. Boxes on the left show forest cover as well as forest near edges and in isolated patches. The bioclimatic zones used for reporting cover and rates of change are provided in the Forest Zones inset. *Credit: G. Harper, Conservation International.*


Forest Cover of Madagascar: 1950s - ~2000
Detail of Cover: 1950s
Detail of Cover: ~2000
Forest Edge Distance: ~2000
km
< 0.06
>3
Forest Patch Size: ~2000
km2
< 5
>1,000
Forest Zones
Dry
Humid
Spiny
Cover: 1970s - ~2000
km
200
150
100
50
0
detail
Cover: 1950s
Forest (~2000)
Non-Forest (1970s)
Clearance (1970s - ~1990)
Clearance (~1990 - ~2000)
Mangroves
Water
Forest (pre-2000) and Cloud (~2000)
Non-Forest (~2000) and Cloud (pre-2000)
Cloud (~2000 and pre-2000)

Ngorongoro Conservation Area. While this was a miniscule amount of cultivation as of 2000, the potential for future increases in population and associated cultivation were modeled to assess impacts on the livelihoods of the population and on the various wildlife populations. Analysis of demographic and satellite data determined a linear relationship between population and area of cultivation. These results were extended into the future using the SAVANNA ecosystem simulation model. The study found that a doubling of the human population would lead to a doubling of the area of cultivation, to approximately 80 km^2 or 1% of the Ngorongoro Conservation Area, which would not have a negative effect on wildlife populations or on the Maasai agro-pastoralists. The work was jointly funded by USAID and NSF.

Fire Information for Resource Management System.[3] Until recently, protected area managers who wanted to use satellite-derived information to monitor fires burning within their area of jurisdiction faced considerable challenges—particularly those working in remote locations and with limited access to the Internet. Protected area managers usually want to know the locations of active fires within relatively small areas, generally their park and its surroundings. They also want this information delivered with minimal file sizes that can be accessed quickly and easily over the Internet. The CCSP Fire Information for Resource Management System is being developed to meet

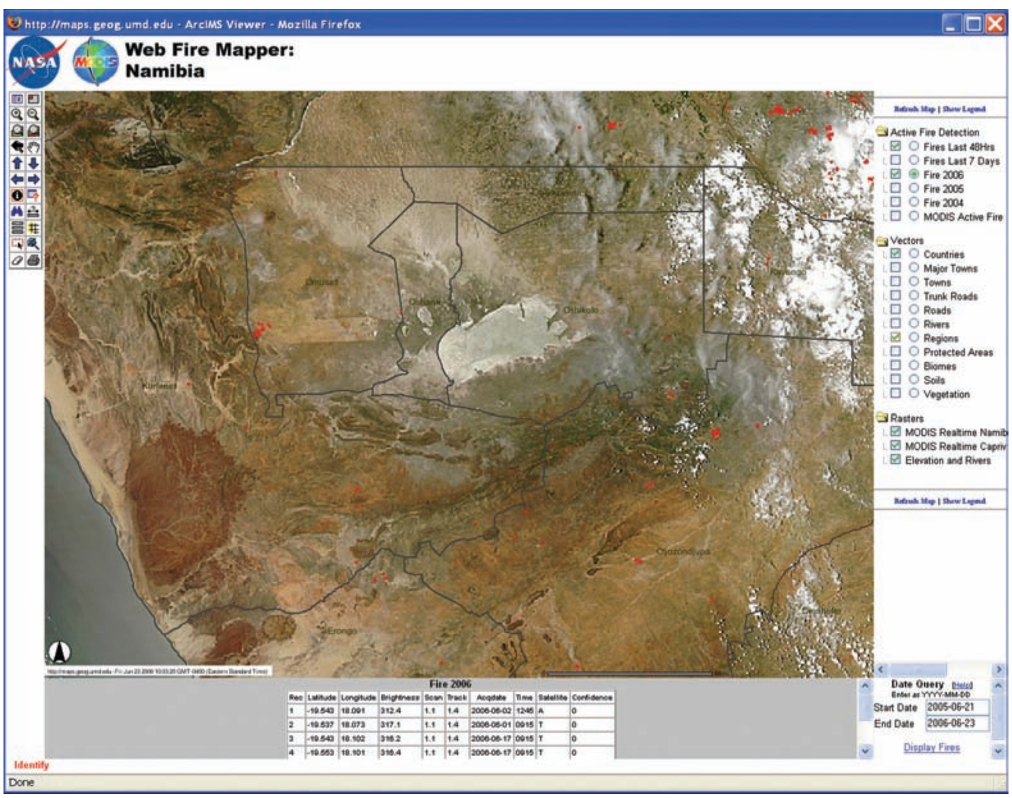


Figure 24: The Fire Information for Resource Management System. This tool provides web-based depictions of MODIS fire products for 1 day, in this case for Namibia. This same information is transmitted by cell phone as a text message to fire wardens in protected areas alerting them to the times and locations of the detected fires. This information has proven very useful for detecting and preventing incursions into protected areas in Africa and elsewhere. *Credit: D.K. Davies, University of Maryland (with permission from GIM International, <http://www.gim-international.com>).*

these requirements in three ways: by providing MODIS active fire information via an interactive web mapping interface; by providing true-color MODIS images, or subsets that show fires burning within specific conservation areas; and by delivering fire alerts through emails and cell phone text messages. Figure 24 provides an example of the interactive web depiction produced by this system.

Rural Sprawl an Important Land-Use Change.[2] Research jointly supported by NASA and USDA provides a comprehensive view of how the Nation's changing socioeconomic characteristics have wrought profound changes in land development, particularly in rural areas of the United States. Using archived data from the censuses of population, housing, and agriculture, the results indicate that one quarter of the 48 contiguous United States now consists of so-called exurban development with low-density housing (6 to 25 homes per km^2). This is a five-fold increase since 1950. The amounts are even higher in the eastern United States. These increases are largely at the expense of agricultural lands. Using remotely sensed data for the southeastern and mid-Atlantic states, the study also found that forest and agricultural land covers have decreased while urban and mechanically disturbed land areas have increased. The relatively widespread growth in U.S. population between 1950 and 2000, coupled with decreasing household sizes and increasing lot sizes, has resulted in major increases in rural sprawl in most regions of the United States, with the possible exception of the Great Plains region (see Figure 25). The information-driven economy has fueled rural sprawl by enabling people to make a living even in relatively isolated areas, including amenity rich areas like the upper Midwest and rural West.

Evidence of Climate Change Due to Historical Practices in Land-Use and Land-Cover Change.[9] The consequences of the land-use and land-cover practices of the ancient Mayans in sustaining a dense population in Central America might be instructive to our survival in a world with shrinking space and resources. They lived in present-day Mexico, Belize, and Guatemala, and maintained a population density of 700 to 800 people per km^2. Recently published research indicates that by AD 800, the Mayans had cut down or deforested all the tropical forests in the surrounding area. They used the wood for buildings, cooking, and manufacturing lime to pave great plazas and roads. The massive deforestation altered the pattern of rainfall, producing or exacerbating periods of drought. Mayan civilization was already in drastic decline when the Spaniards arrived in the 16th century. The present-day tropical forest in this area, once believed to be primeval, is actually only about 600 years old. This is one

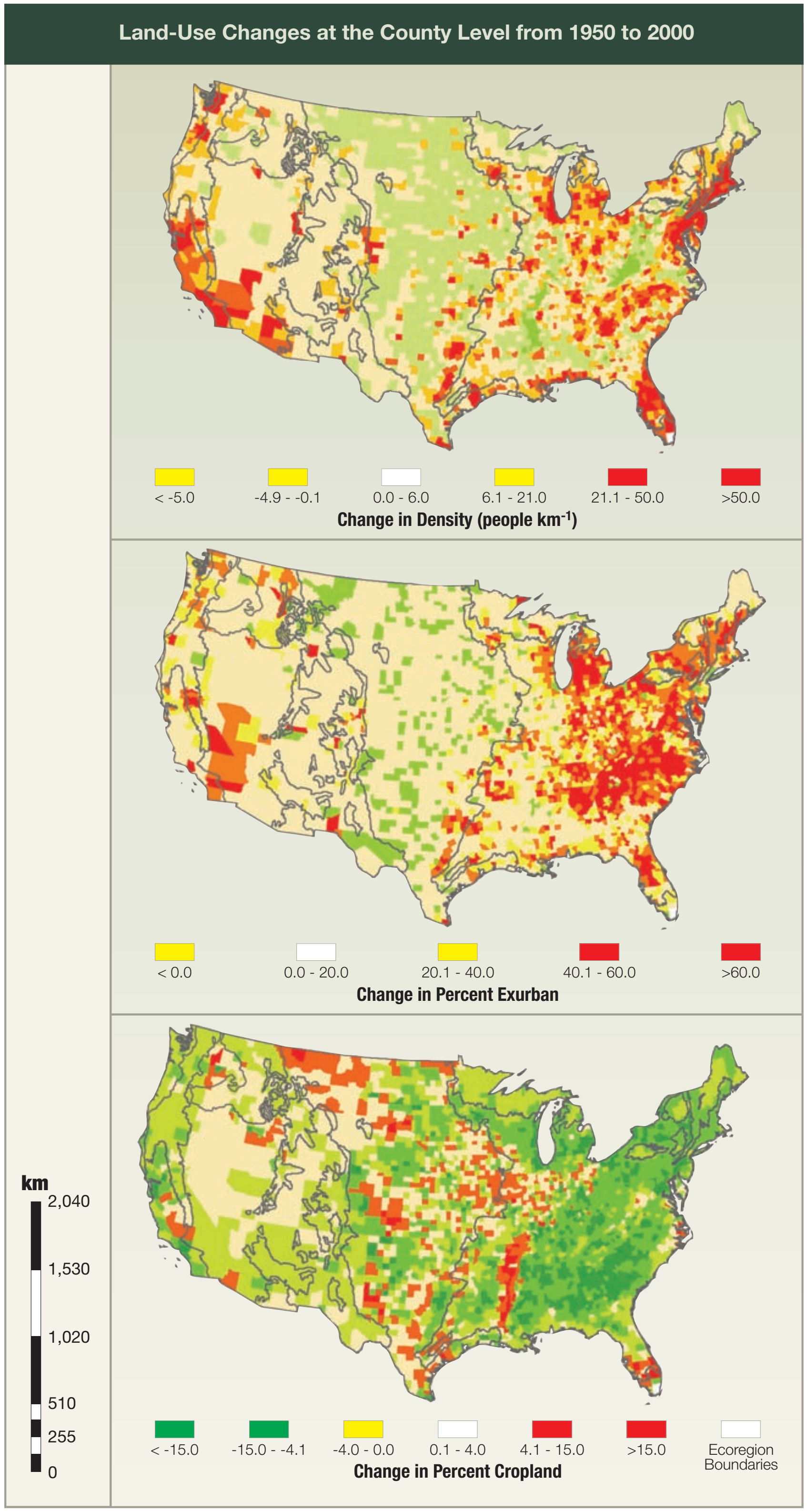
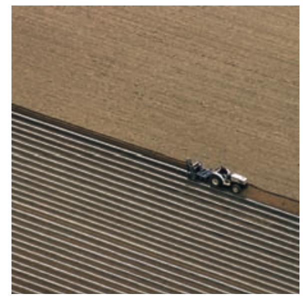


Figure 25: Land-Use Changes at the County Level from1950 to 2000. These products were generated using censuses of population, housing, and agriculture: (top) change in population density; (middle) change in land area settled at "exurban densities" (i.e., 1 house per 1 to 40 acres); and (bottom) change in percentage of cropland. *Credit: D.G. Brown, University of Michigan (reproduced from* ***Ecological Applications*** *with permission from the Ecological Society of America).*

example of historical land-use and land-cover changes that have affected many previous cultures and contributed to their collapse.

Satellite and aircraft remote-sensing techniques were used in this study to find abandoned Mayan cities (see Figure 26), water storage areas, and agricultural fields to document the extent of Mayan occupation of their Central American landscape. The same satellite remote-sensing techniques that are widely used to study present day land-use and land-cover change also play a key role in understanding historical land-use and land-cover change, such as that of the Mayan culture.



Urbanization, Land-Use and Land-Cover Change, and the Carbon Cycle: Consequences for Net Primary Productivity in the United States.[5] Using a combination of daytime and nighttime satellite data and a biophysical model, estimates of the impact of urbanization on net primary production have been made. Nighttime images from the Defense Meteorological Satellite's (DMSP) Operational Linescan system were used to create a thematic map portraying the extent and spatial distribution of urbanized, semi-urbanized, and non-urbanized areas in the lower 48 states (see Figure 27, top panel). The DMSP-based urban categories were geo-registered to a 12-layer map of monthly maximum normalized difference vegetation index values derived from the Advanced Very High Resolution Radiometer (AVHRR) sensor and a digital land cover map. Monthly net primary production values were calculated over the course of a year for all land-cover types and summed to provide a map of total annual net primary production for the United States at 1-km spatial resolution (see Figure 27, lower panel). The net primary production is the product of the Carnegie

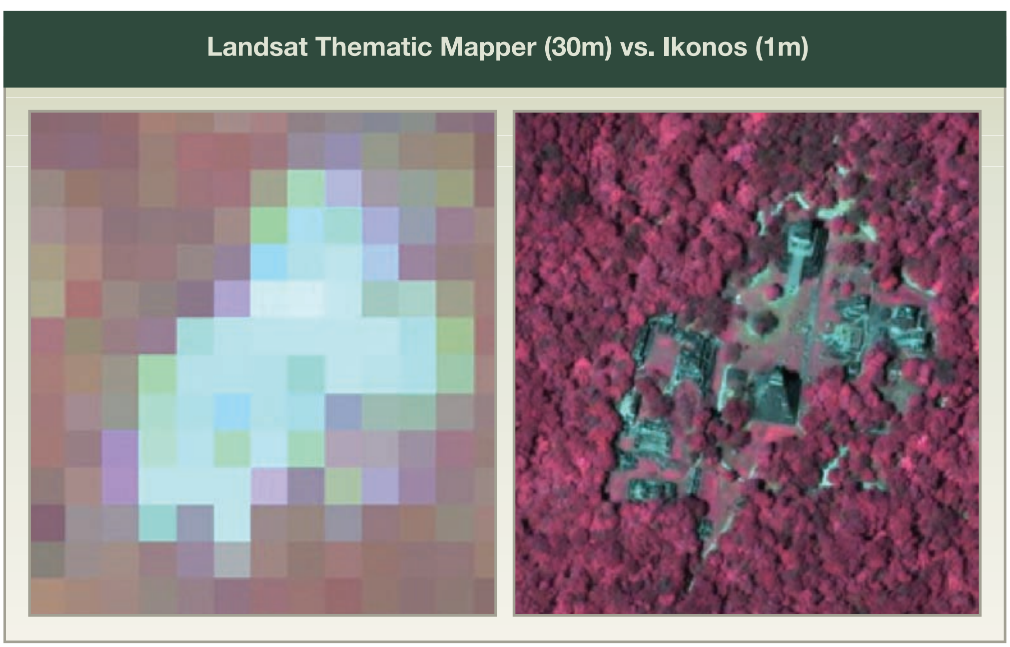


Figure 26: Landsat Thematic Mapper (30m) vs. Ikonos (1m). A side-by-side comparison of Landsat Thematic Mapper 30m (left) and Ikonos 1m (right) false-color imagery shows the ancient ruins of Tikal—a Mayan city deep in the Guatemalan rainforest that was lost for almost 1,000 years. The Ikonos imagery resolution of approximately 1 meter can detect individual pyramids, pathways, and small structures. *Credit: T.L. Sever, NASA/ Marshall Space Flight Center.*

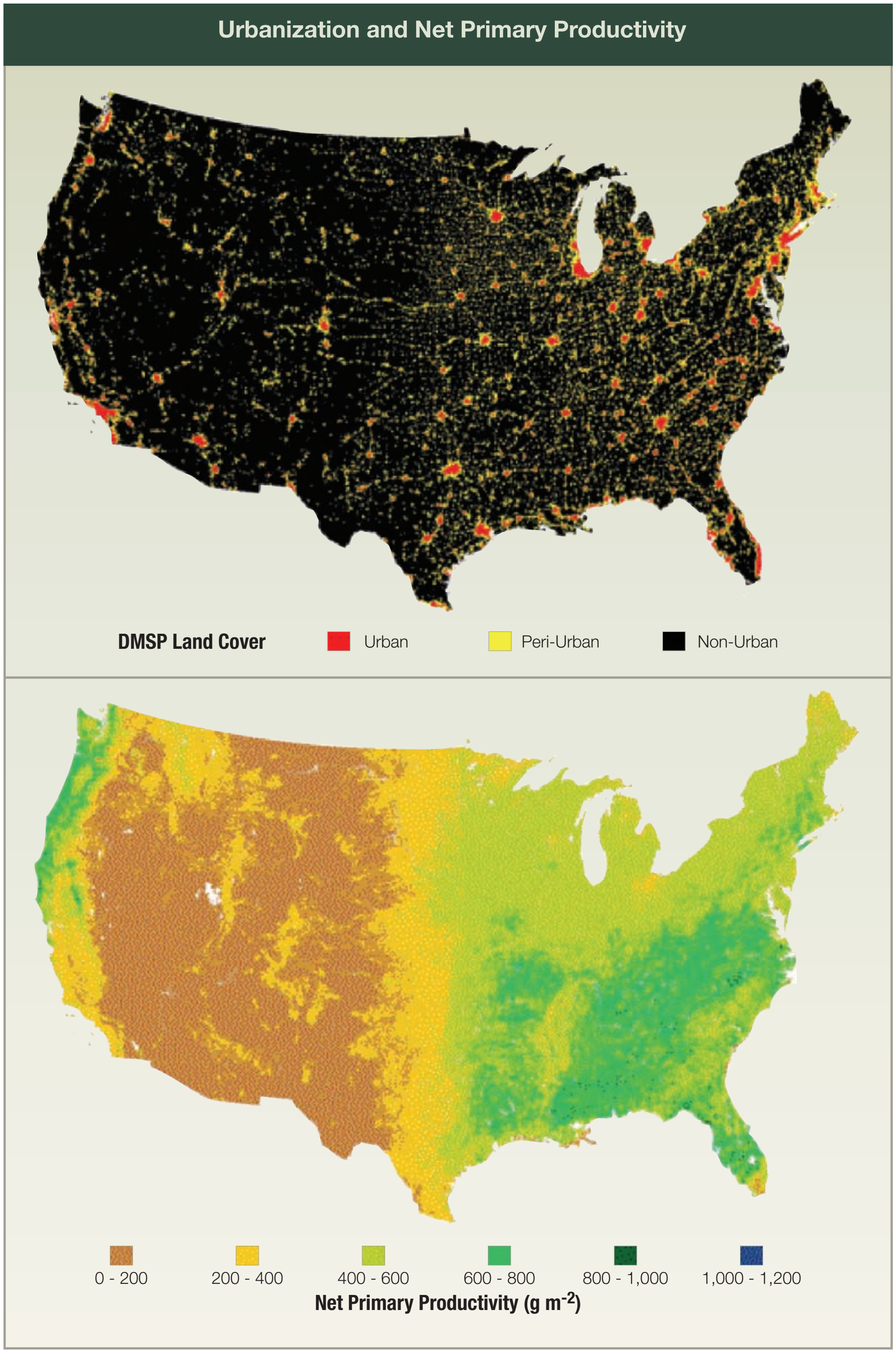


Figure 27: Urbanization and Net Primary Productivity. The top product provides an urbanization map generated from Defense Meteorological Satellite (DMSP) Operational Linescan System data collected from October 1994 to March 1995, showing urban, peri-urban, and non-urban areas. The lower product simulates total annual net primary production for the United States at 1-km spatial resolution. *Credit: M.L. Imhoff,* NASA/ Goddard Space Flight Center *(reproduced from* **Remote Sensing of Environment** *with permission from Elsevier Inc.).*

Stanford Ames Approach (CASA) productivity model driven by 1992-1993 AVHRR data and current climate, and can be considered a "post-urban" representation of the net primary productivity of the land surface.

Most of the urbanization in the United States has taken place on the lands with higher rates of net primary production. The estimated overall reduction of net primary production due to urban land transformation in the United States relative to total pre-urban production is 1.6% per year. The reduction of net primary production from agricultural lands is equivalent to food products capable of satisfying the caloric needs of 16.5 million people or about 6% of the U.S. population.

HIGHLIGHTS OF FY 2007 PLANS

Creation of a 2005-2007 Landsat Data Set.[10] Since 1972, Landsat satellites have collected data that have been invaluable for the quantitative study of land cover, land use, and land-cover change. The ground resolution of the Landsat satellites is ideal for studying a wide range of surface phenomena. In addition, a variety of natural and human land-use changes (e.g., wildfires, deforestation, agricultural activity, glacier expansion/contraction, and urbanization) represent alterations that occur at spatial scales of tens of meters. Therefore, Landsat data are invaluable for studying the land surface and how it affects and is affected by climate. Landsat data from 1972 to 2003 have provided the global coverage required to study land-use and land-cover change. However, a mechanical failure of the Landsat 7 Enhanced Thematic Mapper instrument on 31 May 2003 has degraded subsequent Landsat 7 data, and there are no other globally available Landsat-type data at these spatial scales. This problem will not be completely solved until at least 2011, when a Landsat-like instrument will be launched. This data gap from 2003 to at least 2011 makes it difficult to achieve several key CCSP goals directly related to understanding the direct impact of land-use and land-cover change on climate. U.S. government agencies affected by this include NASA, USGS, USDA, EPA, DOD, HHS, the Federal Emergency Management Agency (FEMA), and NOAA.

CCSP proposes to address this by redirecting existing agency resources in order to acquire a global collection of 2005 to 2007 data from Landsat 5 holdings of International Cooperator ground receiving stations and the U.S. archive; Landsat 7 image pairs from the U.S. archive (wherein the 25% of missing pixels in one scene are filled in from one or more subsequent scenes of the same site); the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER); Earth Observing-1's Advanced Land Imager (EO-1's ALI); and satellites now operated by foreign countries. This CCSP priority item will also be extremely important for scientific studies of the cryosphere, ecosystems, the carbon cycle, and the International Polar Year; thus, it will address multiple CCSP requirements and contribute to improved decision support. NASA and USGS, the two major users of Landsat data, will organize the project, with advice from and participation by other interested Federal agencies.

This activity will address CCSP Goals 1 and 2 and Question 6.1 of the CCSP Strategic Plan.

National Land Cover Data Set 2001. The National Land Cover Database (NLCD) has become the flagship land-cover data product, providing periodic maps showing the patterns and extents of major U.S. land-cover types. Development of NLCD has been coordinated by the Multi-Resolution Land Characteristics Consortium, which is made up of a number of government agencies including USGS (founder and *de facto* leader); EPA; NOAA; the U.S. Forest Service; NASA; the National Park Service; the Natural Resources Conservation Service; the Bureau of Land Management; the U.S. Fish and Wildlife Service; and the Office of Surface Mining. Two land-cover data sets have been undertaken. The first NLCD map, NLCD 1992, was produced through the classification of Landsat satellite imagery acquired around 1992, covers the conterminous United States, and was completed in 2001. The second map, NLCD 2001, uses Landsat images acquired around 2001 and will be completed in 2006. NLCD 2001 is also expanding the geographic coverage of the 1992 data set to include Alaska, Hawaii, and Puerto Rico; this expansion will be completed by 2008.

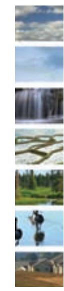
This activity will address CCSP Goals 1 and 2 and Question 6.2 of the CCSP Strategic Plan.

Assessment of Land-Use and Land-Cover Change Numerical Models: A Request for a National Academy of Sciences Study. Land-use and land-cover change are important processes that influence, and are influenced by, the Earth's climate, carbon, water, ecological, and socioeconomic systems. A variety of modeling approaches have been used to understand land-use and land-cover change and to encode that understanding for the purpose of projection and prediction. These approaches include Markov, econometric, micro-simulation, dynamic spatial simulation, cellular automata, agent-based, and a variety of statistical/empirical numerical models.

Attempts to couple land-use change models with models of biogeochemical, water, and ecological processes face a number of challenges. The spatial and temporal scales of land-use change models need to be compatible with both the driving processes of land-use change and models of environmental systems. The land-use and land-cover change models must also share specific semantic, ontological, and technical specifications in order to allow inter-model communication and coupling. Thus, although there has been much research that contributes to our understanding of the dynamics of land-use and land-cover change from an observational or empirical basis, a suite of models of land-use and land-cover changes at spatial scales from local to global, and temporal scales from short (<5 years) to long (>50 years), must be developed. These models must be compatible with environmental models relevant for Federal, State, and local management and policy development.

Land-use change has direct and indirect impacts on the health and sustainability of society and ecosystems. A synthetic understanding of land-use change modeling approaches is needed so that these reciprocal relations can be studied, in the case of explanatory models, and projected using computer-based tools that encode the best scientific understanding and complement the diverse applications used by agency programs. Importantly, the study will provide guidance to a diverse set of science- and application-based model users on the strengths and weakness of the various approaches and the appropriate contexts in which they can be applied. Such guidance is not currently widely available. This study will be conducted by the National Academy of Sciences.

This activity will address CCSP Goals 1 and 2 and Question 6.3 of the CCSP Strategic Plan.



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5 | Global Carbon Cycle

Strategic Research Questions

7.1 What are the magnitudes and distributions of North American carbon sources and sinks on seasonal to centennial time scales, and what are the processes controlling their dynamics?

7.2 What are the magnitudes and distributions of ocean carbon sources and sinks on seasonal to centennial time scales, and what are the processes controlling their dynamics?

7.3 What are the effects on carbon sources and sinks of past, present, and future land-use change and resource management practices at local, regional, and global scales?

7.4 How do global terrestrial, oceanic, and atmospheric carbon sources and sinks change on seasonal to centennial time scales, and how can this knowledge be integrated to quantify and explain annual global carbon budgets?

7.5 What will be the future atmospheric concentrations of carbon dioxide, methane, and other carbon-containing greenhouse gases, and how will terrestrial and marine carbon sources and sinks change in the future?

7.6 How will the Earth system, and its different components, respond to various options for managing carbon in the environment, and what scientific information is needed for evaluating these options?

See Chapter 7 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of these research questions.

Over the past two centuries, fossil-fuel emissions, land-use changes, and other human activities have contributed to atmospheric carbon dioxide (CO_2) and methane (CH_4) concentrations that are unprecedented over the past 650,000 years. Future atmospheric concentrations of these gases will depend on fossil-fuel emissions; uptake, storage, and

U.S. GLOBAL CARBON CYCLE SCIENCE PROGRAM

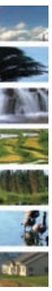
The U.S. Global Carbon Cycle Science Program contributes to all CCSP Goals, focusing particularly on Goal 2: *Improved quantification of the forces bringing about changes in the Earth's climate and related systems*. It directly addresses the global carbon cycle research elements and questions (*CCSP Strategic Plan*, Chapter 7) and is synergistic with the ecosystems, global water cycle, climate variability and change, atmospheric composition, land-use and land-cover change, human contributions and responses, and observations research elements.

release of carbon by Earth's ecosystems; biogeochemical gradients between major carbon reservoirs; and active management activities. Options available to societies for stabilizing or mitigating greenhouse gases in the atmosphere through management of carbon in the environment include reduction of carbon emissions at the source and/or sequestration of carbon through biospheric or geospheric storage and engineered approaches.

In FY 2007, the U.S. Global Carbon Cycle Science Program will continue to address the magnitude and variability of the carbon reservoirs of the North American continent and adjacent ocean basins, and transfers of carbon between the Earth's ecosystems, by characterizing and quantifying the biological, chemical, and physical processes that determine carbon cycling dynamics. Integrating observations, measurements, and models of the atmospheric, terrestrial, and oceanic components of the carbon cycle is the essential core research effort needed to quantify multi-scale carbon budgets, develop successful carbon management strategies, and reduce the uncertainties in carbon cycle dynamics. Through research efforts such as the North American Carbon Program (NACP) and the Ocean Carbon and Climate Change (OCCC) Program, the U.S. Global Carbon Cycle Science Program will continue to provide critical science information on the fate of carbon in the environment and how cycling of carbon may change or be managed in the future. By integrating models, observations, measurements, and experimental results at multiple spatial and temporal scales, we will be better able to quantify carbon budgets, develop successful carbon management strategies,

THE NORTH AMERICAN CARBON PROGRAM

Designed to address strategic research question 7.1, NACP will quantify the magnitudes and distributions of terrestrial, freshwater, oceanic, and atmospheric carbon sources and sinks for North America and adjacent oceans; understand the processes controlling source and sink dynamics; and produce consistent analyses of North America's carbon budget that explain regional and continental contributions and year-to-year variability. NACP is committed to reducing uncertainties related to the buildup of CO_2 and CH_4 in the atmosphere and the amount of carbon, including the fraction of fossil-fuel carbon, being taken up by North America's ecosystems and adjacent oceans.



and reduce the uncertainties about the carbon cycle and changes in atmospheric concentrations of CO_2 and CH_4.

THE OCEAN CARBON AND CLIMATE CHANGE PROGRAM

Designed to address strategic research question 7.2, OCCC will focus on oceanic monitoring and research aimed at determining how much atmospheric CO_2 is being taken up by the ocean at present and how climate change will affect the future behavior of the oceanic carbon sink. NACP and OCCC are synergistic, converging in addressing carbon dynamics in the coastal oceans adjacent to North America and at its land-sea margins, where changes in the terrestrial system greatly influence carbon processes in the coastal ocean.

Activities planned for FY 2007 will focus on integrating observational capabilities, completing monitoring networks that measure carbon fluxes and changes in stocks, conducting manipulative experiments in North America and adjacent oceans, and modeling the carbon cycle for diagnostic and predictive analyses. This integrative approach will include quantification of landscape-scale carbon dynamics, intensive terrestrial measurement campaigns and experimental studies, atmospheric monitoring networks, global ocean carbon survey and inventory, coastal ocean and atmospheric carbon exchange measurements, and model comparisons.

Successful completion of this work will yield, and be measured by, integrated and accessible observational databases; peer-reviewed publications on quantification of carbon budget components and multi-scale carbon cycle processes; more accurate estimates of changes occurring or likely to occur in carbon cycle-related systems; reduced uncertainty in U.S. carbon source and sink estimates; and a stronger scientific basis for developing technical and policy options for managing carbon.

The agencies responsible for CCSP carbon cycle research (DOE, NASA, NIST, NOAA, NSF, USDA, and USGS) have organized a coordinated, interagency, multidisciplinary research strategy to bring together the infrastructure, resources, and expertise essential for providing this information, reducing uncertainties, and producing integrated carbon budget analyses. A developing dialog with stakeholders, including resource managers, policymakers, and other decisionmakers, has been established and will be maintained to ensure that the information provided is effective.

HIGHLIGHTS OF RECENT RESEARCH

The following are selected highlights from the participating CCSP agencies that support a multitude of land, ocean, atmosphere, and remote-sensing projects on the carbon cycle. These science highlights describe progress contributing to the goals of the *CCSP Strategic Plan*.

Synthesis, Analysis, and Modeling

Cumulative Carbon Dioxide Emissions.[8] Global emissions from fossil-fuel consumption and cement manufacture reached an all-time high of approximately 7 billion metric tons of carbon in 2002. Since 1751, over 297 billion metric tons of carbon have been released to the atmosphere from human use of fossil fuels and cement production, with half these emissions occurring since 1978. Globally, consumption of crude oil and coal account for almost 77% of fossil-fuel CO_2 emissions. Combustion

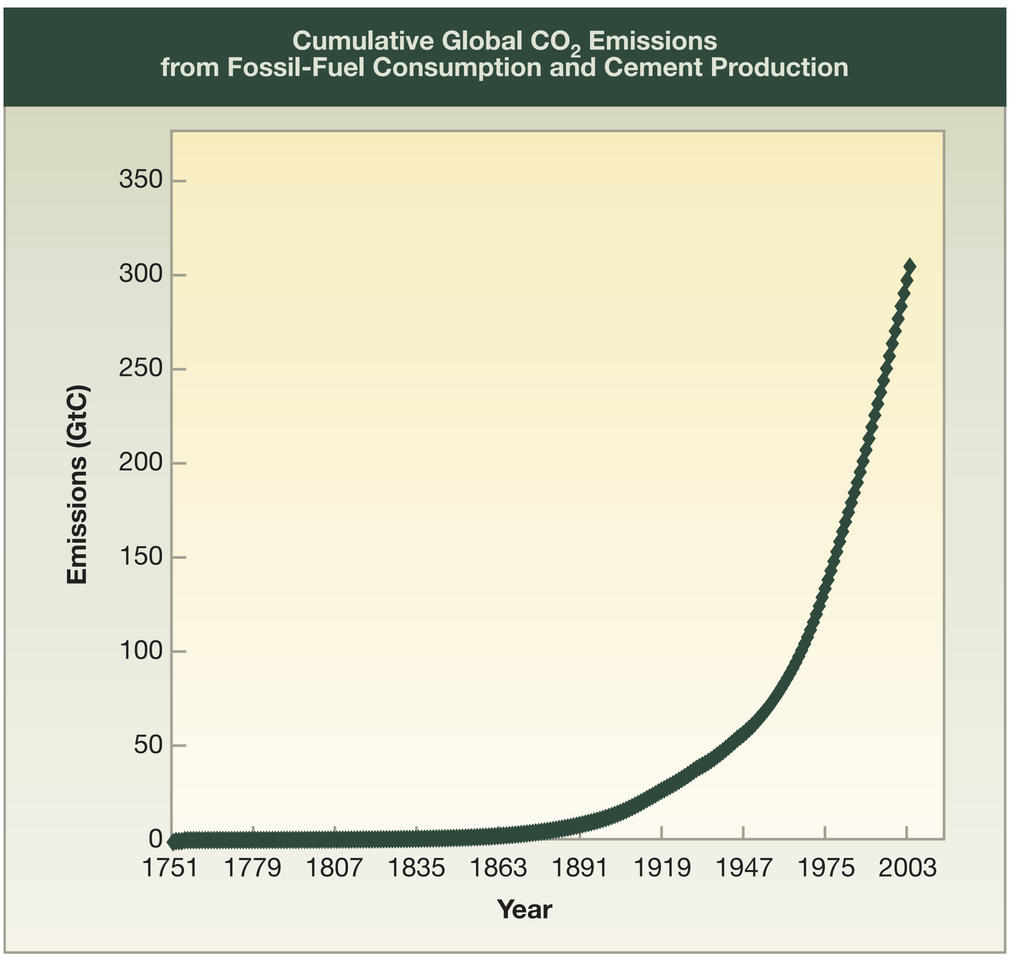
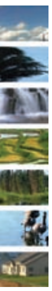
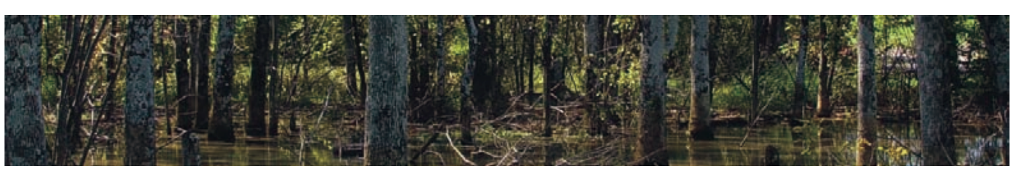


Figure 28: Cumulative Global CO_2 Emissions from Fossil-Fuel Consumption and Cement Production. This chart provides cumulative global fossil-fuel CO_2 emissions from 1751 to 2003. *Credit: T.A. Boden, DOE/Oak Ridge National Laboratory.*

of gas fuels (e.g., natural gas) accounted for 19.3% (1.4 billion metric tons of carbon) of the 2002 total, which reflects a gradually increasing global utilization of natural gas. Releases during cement production have doubled since the mid-1970s and now contribute about 0.25 billion metric tons of carbon per year globally. Twenty nations generate roughly 80% of global fossil-fuel CO_2 emissions (see Figure 28).



Modeling the Carbon Cycle in a Changing Climate.[5] Simulations were conducted over the period 1820-2100 using the National Center for Atmospheric Research (NCAR) Community Climate System Model fully coupled to a land carbon cycle model and an ocean carbon cycle model with marine biology and carbonate chemistry (NCAR carbon-CSM1.4). The simulations show decreases in both terrestrial and oceanic uptake of fossil-fuel CO_2 as rates of fossil-fuel emissions rise and greenhouse gas increases affect global climate. Such changes in carbon sinks in turn affect climate through their influences on atmospheric CO_2 and its radiative forcing and thus represent an important feedback within the coupled carbon cycle and climate systems. Warming affects air-sea exchange, oceanic circulation, and ocean biology. Compared to simulations with constant CO_2 radiative forcing, in 2100 the fully coupled model forced by "business-as-usual" fossil-fuel emissions has 1.2 K higher globally averaged sea surface temperature, 17% slower North Atlantic overturning, and 5% lower global efflux of CO_2. These effects lead to approximately 20 Gt (1 Gt = 10^9 metric tons) less total carbon in the oceans in the fully coupled simulations. On land, the fully coupled simulation has less net carbon uptake in the tropics and greater uptake at high latitudes than with constant CO_2 radiative forcing. These regional differences approximately offset each other such that there is only about 20 Gt difference between total terrestrial carbon sinks in the two simulation experiments. Overall, climate-carbon feedbacks within the NCAR carbon-CSM1.4 model are similar to those in other models (e.g., the Hadley Centre model), albeit with weaker sensitivity. In the NCAR model, the climate sensitivity to a doubling of atmospheric CO_2 is lower than for other models. As a result, warming and drying are not as severe and have less impact on photosynthesis and plant mortality in the tropics. Finally, turnover times of terrestrial carbon pools affect the longevity and magnitude of land sinks, and the more rapid turnover of terrestrial carbon in NCAR carbon-CSM1.4, validated by the simulation of the contemporary atmospheric CO_2 cycle, leads to a weaker sink on land with less sensitivity to climate (see Figure 29).



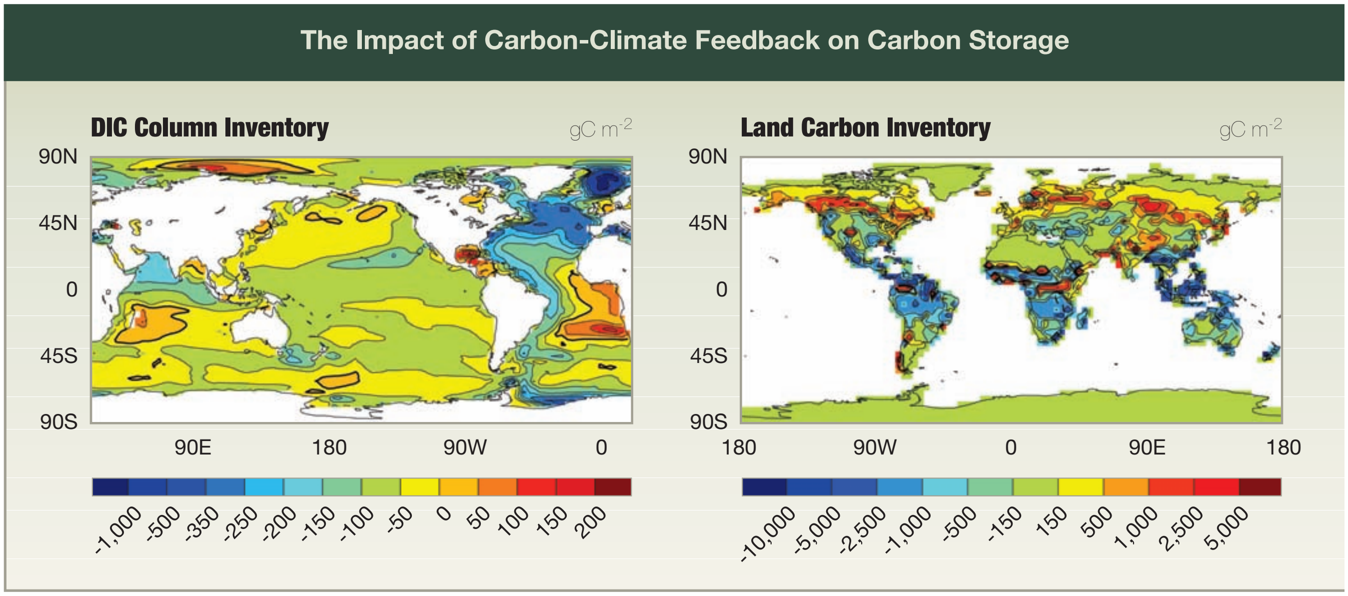


Figure 29: The Impact of Carbon-Climate Feedback on Carbon Storage. These products illustrate the impact of carbon-climate feedback on carbon storage in oceanic (left panel) and terrestrial (right panel) systems. Units are grams carbon m^{-2}; DIC = dissolved inorganic carbon. *Credit: I.Y. Fung, University of California; S. C. Doney, Woods Hole Oceanographic Institution; K. Lindsay, National Center for Atmospheric Research; and J. John, University of California (reproduced from* **Proceedings of the National Academy of Sciences** *with permission from the National Academy of Sciences).*

Influence of Land-Cover Change on the Carbon Cycle.[24] Land-surface processes influence the atmospheric carbon budget, with implications for the dynamics of Earth's climate system, ecosystem sustainability, and human well-being. Land-use changes such as forest cutting and regrowth, urbanization, and the development, abandonment, and management of agricultural land can all affect how much carbon is stored in plants and the soil. Merged data sets have been used to analyze and quantify the rates and causes of land-use and land-cover change for more than 3,000 study areas across the Nation. The land-use changes are used as inputs to models of the carbon cycle, resulting in maps of areas that remove CO_2 from or release CO_2 to the atmosphere. The results show that forest regions of the southeastern United States have been removing CO_2 from the atmosphere, but at a decreasing rate. In the northwestern Great Plains between 1972 and 2001, the modeling indicated that soil carbon stocks increased by nearly 4 metric tons per hectare. The carbon dynamics of other regions are being investigated as the land-cover change data become available. When complete, the influence of land-cover change on carbon dynamics from the 1970s to the present will be mapped for the conterminous United States. The research integrates many data sources to understand how land management affects atmospheric concentrations of greenhouse gases, and thus contributes to climate change (see Figure 30).

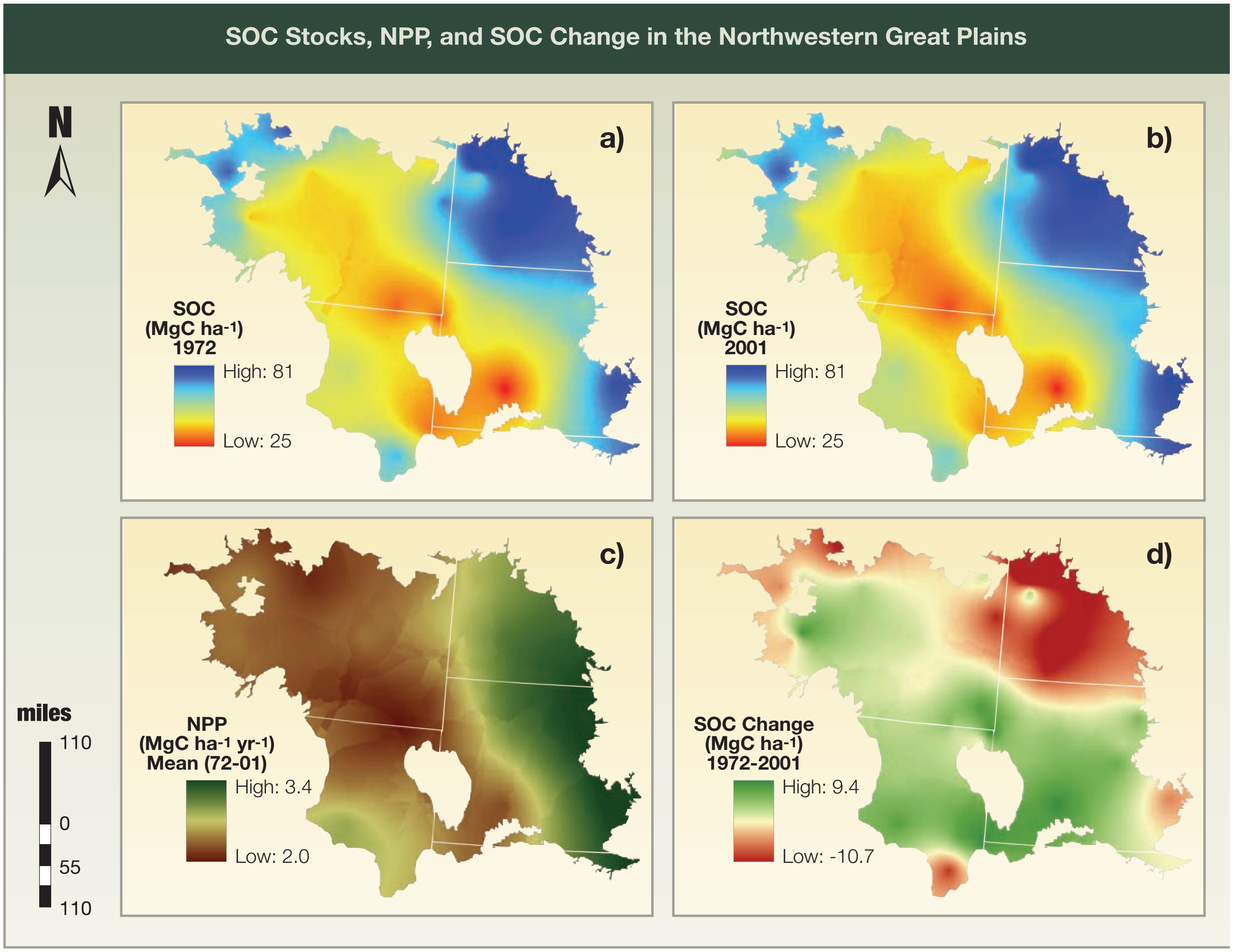


Figure 30: SOC Stocks, NPP, and SOC Change in the Northwestern Great Plains. These products provide spatial distribution patterns of soil organic carbon (SOC) stocks, net primary production (NPP), and SOC change in the northwestern Great Plains (portions of Montana, Nebraska, North Dakota, South Dakota, and Wyoming) between 1972 and 2001: (a,b) the spatial distributions of total SOC stocks in 1972 and 2001, respectively; (c) the annual average NPP between 1972 and 2001; and (d) the change in SOC stocks from 1972 to 2001, with positive values indicating an increase in SOC stocks over this period. *Credit: Z. Tan, South Dakota Center for Biocomplexity Studies; S. Liu, SAIC; C.A. Johnston, South Dakota Center for Biocomplexity Studies; T.R. Loveland, U.S. Geological Survey; L.L. Tieszen, U.S. Geological Survey; J. Liu, U.S. Geological Survey; and R. Kurtz, U.S. Geological Survey (reproduced from* ***Global Biogeochemical Cycles*** *with permission from the American Geophysical Union).*

Global Modeling Estimates of Ocean Carbon Production.[2] Researchers compared 24 models that estimate depth-integrated primary production from satellite measurements of ocean color and seven models that use general circulation models coupled with ecosystem or biogeochemical models. The model results varied the most for the Southern Ocean, sea surface temperature under 10°C, and chlorophyll concentration exceeding 1 mg m^{-3}. Based on the conditions under which the model results varied the most, researchers concluded that current models based on ocean color are challenged by high nutrient-low chlorophyll conditions and extreme temperatures or chlorophyll concentrations. Although current models are very useful, further progress in primary production modeling requires improvements in understanding the effect of temperature on photosynthesis and in parameterizing the maximum photosynthetic rate.

Carbon Exchange between Terrestrial Ecosystems and the Atmosphere

Isolating the Effect of Vegetation on Net Ecosystem Carbon Exchange.[15,23] The Ameriflux network, established in 1996, provides continuous observations of ecosystem level exchanges of CO_2, water vapor, energy, and momentum spanning diurnal, synoptic, seasonal, and interannual time scales. Researchers isolated the effect of vegetation on net ecosystem exchange of CO_2 by observing carbon fluxes in adjacent AmeriFlux sites within each of three vegetation types representing the main successional stages in the uplands of the southeast United States. Contrary to expectations, researchers found that the mean annual net ecosystem exchange in the mature forest was not lower than that of the fast-growing plantation. Year-to-year variation in water availability showed that the pine plantation was better equipped than the broadleaf forest to profit from peak wet periods but was also more susceptible to drought. Preliminary scaling of the three-site data to a 100-km^2 area demonstrates the effect of water availability on the average net ecosystem exchange. Net ecosystem exchange of the plantation stands increased 33% in a wet year and decreased by 21% in a dry year.

Carbon Losses from High-Elevation Mountain Forests.[10,11,20] Scientists used a model-data synthesis approach to extract process-level information from multiple years of eddy covariance measurements of net ecosystem exchange of CO_2 at an AmeriFlux subalpine forest ecosystem. They found that photosynthesis, and possibly leaf respiration, are down-regulated when the soil is frozen, and the metabolic

processes of soil microbes vary in the summer and winter because of the existence of distinct microbial communities. Soil respiration was observed to be exceptionally sensitive to small changes in beneath-snow soil temperature, meaning that small changes in snow amount can cause large changes in the amount of CO_2 lost from

Figure 31: The Niwot Ridge Ameriflux Site, Colorado. Studies of soil carbon fluxes beneath the snowpack of the Niwot Ridge Ameriflux site have shown that recent declines in the snowpack of the western United States are likely to affect the flux of CO_2 from the soil to the atmosphere. This research illustrates the tight coupling between the water and carbon biogeochemical cycles in mountain ecosystems. *Credit: S. Burns, National Center for Atmospheric Research.*

mountain forest ecosystems. Using DNA sequence analyses and studies of microbial growth kinetics, the researchers showed that the high sensitivity of soil CO_2 loss to changes in snow depth, and concomitant change in soil temperature, is caused by a uniquely adapted soil microbial community that exhibits exponential growth and high rates of substrate utilization at the cold temperatures that exist beneath the snow (see Figure 31).

Soil Respiration in Ecosystem Carbon Balance.[19] Researchers reviewed the role of soil respiration in determining ecosystem carbon balance, and the conceptual basis for measuring and modeling soil respiration, a significant component of ecosystem respiration. Because autotrophic and heterotrophic activity belowground is controlled by substrate availability, soil respiration is strongly linked to plant metabolism, photosynthesis, and litter fall. This link dominates both base rates and short-term fluctuations in soil respiration and suggests many roles for soil respiration as an indicator of ecosystem metabolism. However, the strong links between above- and below-ground processes complicate the use of soil respiration to understand changes in ecosystem carbon storage. Root and associated mycorrhizal respiration account for roughly half of soil respiration, with much of the remainder derived from decomposition of recently produced root and leaf litter. Changes in the carbon stored in the soil generally contribute little to soil respiration, but these changes, together with shifts in plant carbon allocation, determine ecosystem carbon storage belowground and its exchange with the atmosphere.

Elevated CO_2 Concentration Increases Terrestrial Photosynthesis and Productivity.[6,14] Free-Air CO_2 Enrichment (FACE) research technology creates a platform for multidisciplinary, ecosystem-scale research on the effects of elevated atmospheric CO_2 concentrations over extended periods. FACE experiments are providing unique information on the productivity and carbon processes of ecosystems, and the results are being used in prognostic models to evaluate ecosystem responses to rising atmospheric CO_2 concentration and climate change. Most field experiments are carried out at approximately 550 parts per million (ppm) of CO_2, which is roughly 170 ppm above the ambient concentration (380 ppm). An analysis on the net primary productivity (above- and below-ground) response in four FACE experiments in forest stands found that the response to CO_2 is highly conserved across a broad range of productivity, with a median increase in production of 23 ± 2%. Belowground, meta-analysis of 35 experimental observations from diverse temperate ecosystems indicated that CO_2 enrichment increased soil carbon by an average of 5.6% over 2 to 9 years. Researchers also directly measured similar increases in soil carbon in two experiments where the vegetation responded to CO_2 enrichment with large increases in the production of root litter. Over half of the accrued carbon was protected by incorporation into microaggregates. These findings indicate that the carbon storage capacities of many soils, including some with large organic matter stocks, may not be saturated at present and might be capable of serving as carbon sinks if detrital inputs increase as a result of passive CO_2 fertilization or active management efforts to sequester carbon. The surprising consistency of responses across diverse sites provides a benchmark for predicting ecosystem response, and research can now focus on unresolved questions about carbon partitioning and retention, and spatial variation in the response of net primary productivity caused by availability of other growth-limiting resources.

Regulation of Carbon Sequestration under Elevated Atmospheric Carbon Dioxide.[3,4,7] Researchers have made substantial progress in past years toward understanding nitrogen regulation of carbon sequestration. For example, it was found that spatial variability in soil nutrients, primarily nitrogen, had a dominant impact on how fast the canopy of pines developed after seedlings were planted. Areas where nitrogen was limiting had a less-developed pine canopy and slower carbon sequestration by the pine. Higher atmospheric CO_2 concentration increased canopy leaf area and carbon sequestration, with the increase being proportionally smaller where nitrogen was limiting. The immobilization of nitrogen in woody biomass depletes soils of mineralizable nitrogen, leading to progressive nitrogen limitation of net primary productivity at elevated CO_2 levels. In a metadata analysis of the literature on nitrogen limitation of ecosystem carbon sequestration, it was found that at elevated CO_2 concentrations, significant increases in averaged carbon and nitrogen contents occurred in the plant, litter, and soil pools, leading to more net carbon and nitrogen accumulations in ecosystems. The analysis suggests that complete down-regulation of CO_2 stimulation of plant growth and carbon sequestration is not pervasive across ecosystems and that net nitrogen accumulation probably supports long-term carbon sequestration in response to rising atmospheric CO_2 concentration. Researchers also noted that belowground microbes showed a shift in activity from the decomposition of labile carbon substrates to more recalcitrant carbon substrates, indicating a decline in labile carbon inputs to the soil under elevated CO_2 and progressive nitrogen limitation.

Impact of Land Use on Carbon Sources and Sinks

Carbon Sequestration across Forested Ecosystems.[17] A cross-site vegetation and land-use analysis of eight forested sites from Ontario, Canada, to Mississippi shows that ecosystem carbon sequestration averaged 2.5 metric tons per hectare per year. Carbon sequestration in soils, on the other hand, averaged 10 to 30% of this value, with some notable losses. The use of system-wide averages rather than site-specific data would therefore produce very significant errors. Future predictions and management scenarios will require that site-specific controls be used to model changes in landscape carbon dynamics. Calcium and nitrogen availability were major controls of carbon dynamics, suggesting the possibility of improvements in the management of forested systems.

Carbon Budget Effects of Selective Logging in Tropical Forests.[1] Remote sensing has been used to quantify tropical deforestation and make substantial reductions in uncertainties concerning the contribution of tropical land-use change to the global carbon budget. However, uncertainties remained regarding the effects of selective logging, previously considered undetectable in satellite imagery. Selective logging is the cutting of a limited number of marketable trees, with logs transported off-site. U.S.-sponsored investigations within the international Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) applied new spectral unmixing methods, developed using the EO-1 Hyperion satellite sensor, to Landsat imagery for the top five timber-producing states of the Brazilian Amazon. The development of a robust library of forest spectral signatures using Hyperion observations and the use of pattern-recognition techniques customized for logging patterns in Brazil enabled detailed discrimination of selective logging in an almost fully automated process. The researchers combined their logging results with field-based forest-canopy gap-fraction and roundwood-extraction data to calculate the total wood-extraction rates and carbon losses. Total carbon losses

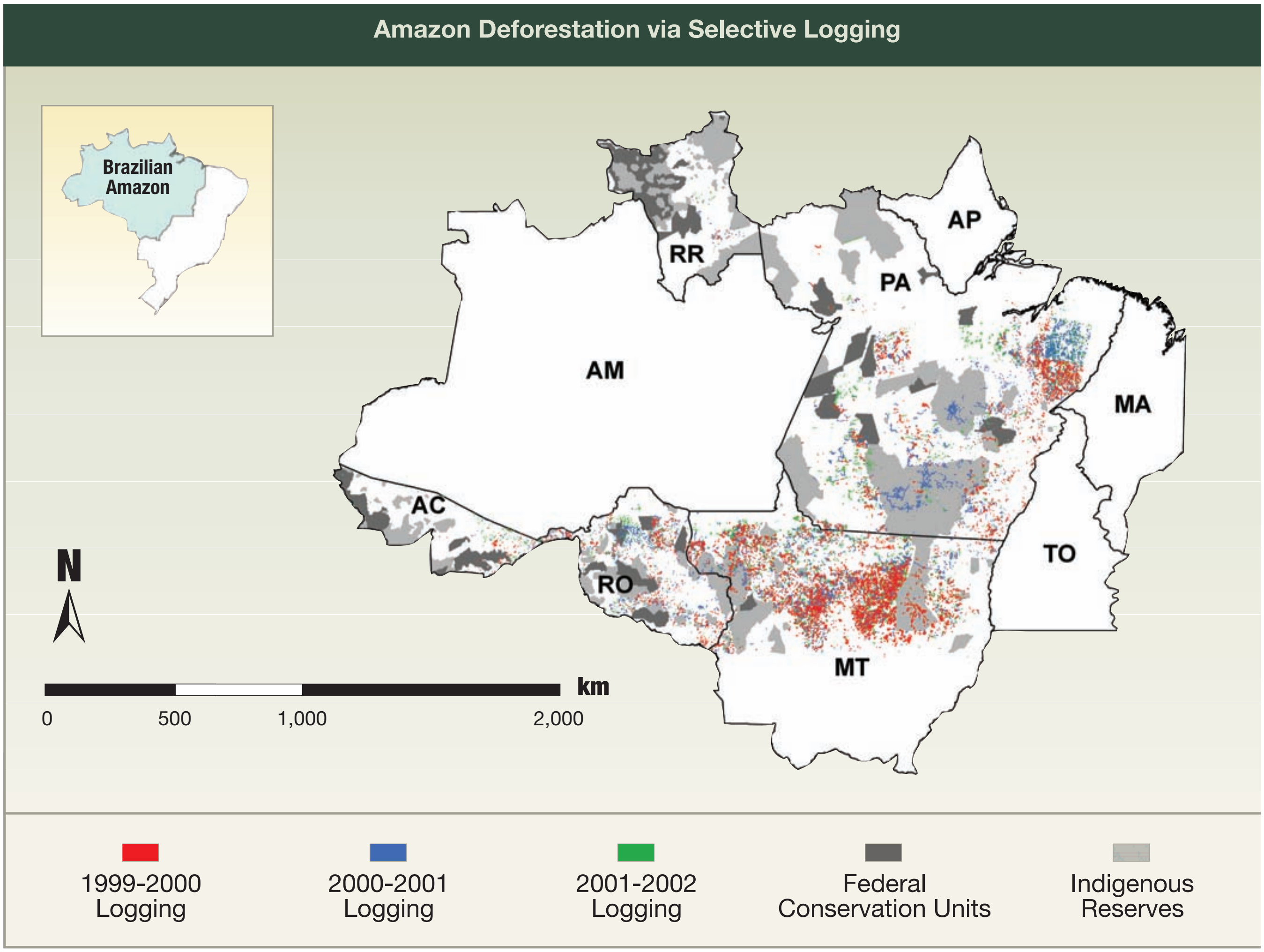


Figure 32: Amazon Deforestation via Selective Logging. Remote sensing has measured Amazon deforestation for three decades, but selective logging has been mostly invisible to satellites. A new large-scale, high-resolution, automated remote-sensing analysis of selective logging was conducted for the top five timber producing states of the Brazilian Amazon. Logged areas ranged from 12,075 to 19,823 km^2 yr^{-1} (±14%) between 1999 and 2002, equivalent to 60 to120% of previously reported deforested area. In 2000, 2001, and 2002, roundwood production averaged 49.8, 29.8, and 26.6 million m^3, respectively. The total volume harvested equaled 10 to 15 MtC. In addition to roundwood, residual stumps, branches, foliage, and roots are left to decompose in the forest, subsequently returning to the atmosphere as CO_2 over approximately a decade. Each year 27 to 50 million m^3 of wood were extracted, and a gross carbon flux of about 0.1 Gt was destined for release to the atmosphere as a result of logging. *Credit: G.P. Asner, Carnegie Institution of Washington; D.E. Knapp, Carnegie Institution of Washington; E.N. Broadbent, Carnegie Institution of Washington; P.J.C. Oliveira, Carnegie Institution of Washington; M. Keller, University of New Hampshire; and J.N. Silva, Empresa Brasileira de Pesquisa Agropecuária-Amazonia Oriental (reproduced with permission from* **Science***).*

were approximately 8 metric tons per hectare contained in roundwood and 34 to 50 metric tons per hectare associated with fine and coarse debris. Integrated to the regional scale, this represents a gross loss of carbon from the forest of about 0.1 Gt for each year of logging. This value increases the estimated gross annual anthropogenic loss of carbon from Amazonian forests by up to 25% over carbon losses from deforestation alone (see Figure 32).

Deforestation Monitoring for Decision Support in Brazil.[12] In a related study, data products developed by LBA researchers using observations from the Moderate Resolution Imaging Spectroradiometers (MODIS) on the Terra and Aqua satellites are being used in Brazil to conduct near-real-time monitoring of deforestation to alert government authorities and the public to unknown and sometimes illegal locations of forest clearing. One system, called DETER, focuses on the legal Amazon; another called SAID also includes the woodlands and savannas to its south. This information is being used by regulatory agencies in Brazil for rapid response and by private conservation organizations interested in the prevention and control of deforestation.

Effects of Fire Behavior and Burn Severity on Carbon Emissions in Boreal Forests.[9] Wildfire is a major disturbance in boreal ecosystems, and changing climate has great potential to alter fire behavior, fuel consumption, and the resultant emissions to the atmosphere. Research on seven experimental prescribed fires on dry Scotch pine (*Pinus sylvestris*) sites in central Siberia showed a large range in fuel consumption and carbon emissions (4.8 to 15.4 metric tons of carbon per hectare) in surface fires, indicating the variability of burning conditions and fire behavior, and a loss of 18 to 23 metric tons of carbon per hectare in crown fires. Currently, fires in these pine forests are dominated by relatively frequent (30 to 50 years), low-severity surface fires. Any increase in the annual area burned by high-severity surface fires or crown fires due to changing climate will affect both short-term carbon storage and fire-related emissions of CO_2 and other greenhouse gases (see Figure 33).

Figure 33: Variations in Surface Fire Intensity in Boreal Scotch Pine Forests. Variations in surface fire intensity cause a wide range of fuel-consumption, fire emissions, and ecosystem fire effects. *Credit: S.G. Conard, U.S. Department of Agriculture Forest Service.*

Ocean Carbon Processes

Impact of Carbon Dioxide Changes on Biological Processes in Adjacent Ocean Basins.[16] An international team of researchers assessed the impacts of changes in ocean chemistry driven by atmospheric CO_2 on ocean biology, particularly carbonate-based biology, in the context of a changing climate or increasingly acidic global ocean. Model simulations indicate that future emissions of CO_2 could cause an increase in ocean acidity by the end of this century. This would affect many biological organisms that require carbonate to build their hard outer shells, a major biological carbon sink in the ocean. Thus a chemical shift in the carbonate system to a more acidic equilibrium would change the growth rate and pattern of the affected organisms, or dissolve the carbonate component of their shells, which would likely lead to death. Corals within reef structures are among the carbonate organisms most likely to be affected. Coral reefs are critical for marine fisheries, providing habitat and nursery grounds.

Fate of Carbon Particles in the Ocean.[18] Sinking particulate matter, such as diatom shells and zooplankton excretions, is the major process for exporting carbon from the sea surface to the ocean interior. During its transit toward the sea floor, most particulate organic carbon (>90%) is returned to inorganic form and redistributed in the water column. The ability to predict quantitatively and mechanistically the depth profile of remineralization is critical for predicting the response of the global carbon cycle to environmental change. Novel techniques are now being used to investigate the depth profile of mineralization, with the unexpected finding that average sinking velocity changes little with depth between 200 and 1800 m, despite the decrease in percent particulate organic carbon. If these observations can be generalized, they signify that through aggregation and disaggregation processes, particle size and sinking velocity adjust to changes in particle density, always yielding the same sinking velocity spectrum. This suggests that remineralization time is directly proportional to depth in remineralization profiles and enables calculation of absolute rates.

Global Continental Margins are Significant Carbon Sinks.[13] Current models of ocean carbon cycling generally stop at the continental shelf break, with little or no exchange between the ocean and the continental margins. Using satellite data to compute annual global net primary production between 1998 and 2001, researchers derived the global particulate organic carbon flux settling below the permanent thermocline and to the seafloor using an empirical model of particulate organic carbon remineralization. Although the margins accounted for 40% of the particulate organic carbon flux from the thermocline, the shallower depth of the marginal seas means that a larger fraction is buried in shelf sediments and a smaller fraction is recycled to CO_2.

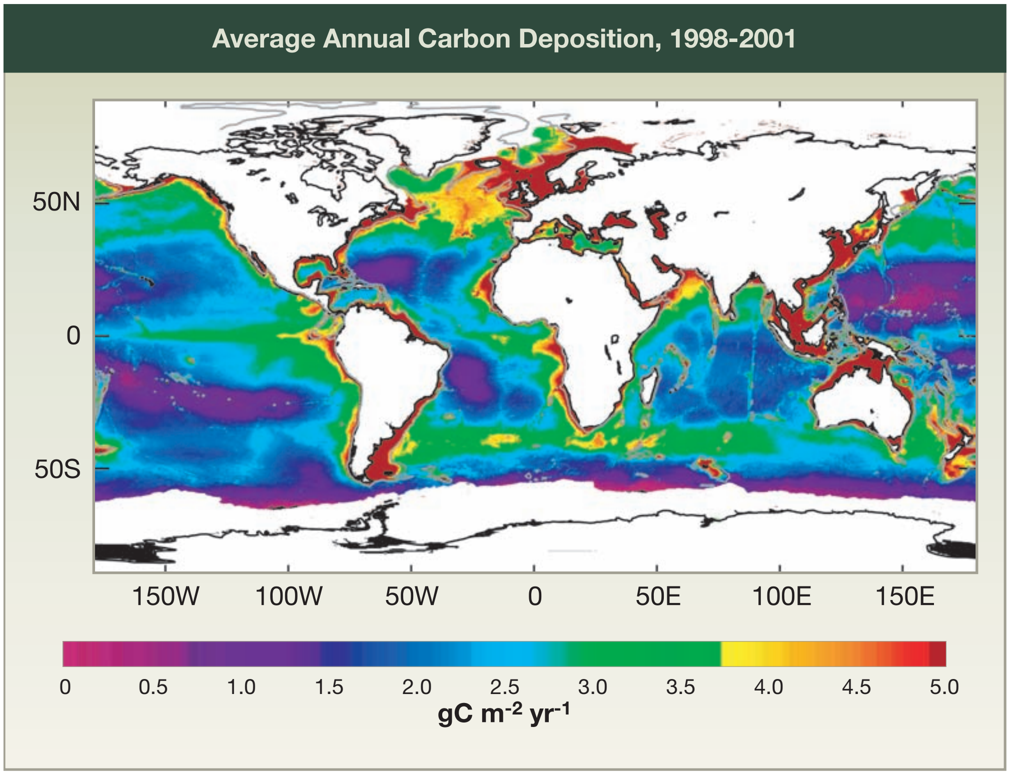
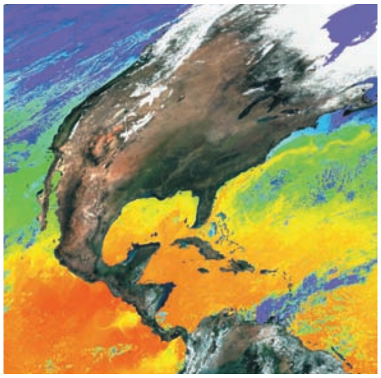


Figure 34: Average Annual Carbon Deposition, 1998-2001. This product estimates average annual particulate organic carbon flux (in gC m^{-2} yr^{-1}) deposited on the ocean bottom between 1998 and 2001, with continental margins outlined in white at the 2,000-m depth contour. *Credit: F.E. Muller-Karger, University of South Florida; R. Varela, Estación de Investigaciones Marinas de Margarita; R. Thunell, University of South Carolina; R. Luerssen, University of South Florida; C. Hu, University of South Florida; and J.J. Walsh, University of South Florida (reproduced from* **Geophysical Research Letters** *with permission from the American Geophysical Union).*

Approximately 67% of the total ocean flux to the sediments occurs over the continental margins, and at least 0.06 Gt of carbon per year (about 40% of the ocean flux) may be buried on continental margins. These regions must be accounted for in realistic models of the global carbon cycle and its linkages to climate change (see Figure 34).

Changes in Dissolved Organic Carbon Export to the Ocean by Arctic Rivers.[22] Climate warming is having a dramatic effect on the vegetation distribution and carbon cycling of terrestrial subarctic and Arctic ecosystems. Researchers presented hydrologic evidence that warming is also affecting the export of dissolved organic carbon and bicarbonate at the large-basin scale. In the Yukon River Basin, flow-adjusted dissolved organic carbon export significantly decreased during the growing season from 1978-1980 to 2001-2003, indicating a major shift in the transfer of carbon from terrestrial to aquatic systems. Researchers concluded that decreased dissolved organic carbon export, relative to total summer and autumn water discharge, results from an increased flow path from soil to surface waters, longer residence times, and microbial mineralization of dissolved organic carbon in the soil active layer and groundwater aquifer. Counter to other predictions, researchers argued that continued warming could result in decreased dissolved organic carbon export to the Bering Sea and Arctic Ocean by major subarctic and Arctic rivers due to increased respiration of organic carbon on land.



Characterization of Carbon Matter in Coastal Ocean Ecosystems.[21] Different algorithms are used with data from satellite-based sensors to retrieve ocean-based properties. One critical ocean property for ecological and biogeochemical research is the carbon-based biomass of primary producers, or biomass from phytoplankton chlorophyll *a*. As shown in Figure 35, two statistically similar phytoplankton chlorophyll *a* algorithms were compared to test how well the two algorithms retrieved the biologically and biogeochemically invaluable phytoplankton biomass property. Data from the comparison of the two algorithms in the global climatology showed that chlorophyll *a* concentrations differ, with the percentage differences approaching 100% at high latitudes. There is a strong relationship between the difference in phytoplankton chlorophyll *a* concentrations and colored dissolved organic material (CDOM) concentrations, indicating that the currently used empirical algorithm overestimates chlorophyll *a* in regions of high CDOM. The bias is caused by the fixed CDOM/chlorophyll *a* relationship in the algorithm, and thus there is an overwhelming need for new satellite technology to better discriminate between chlorophyll *a* and CDOM fractions.

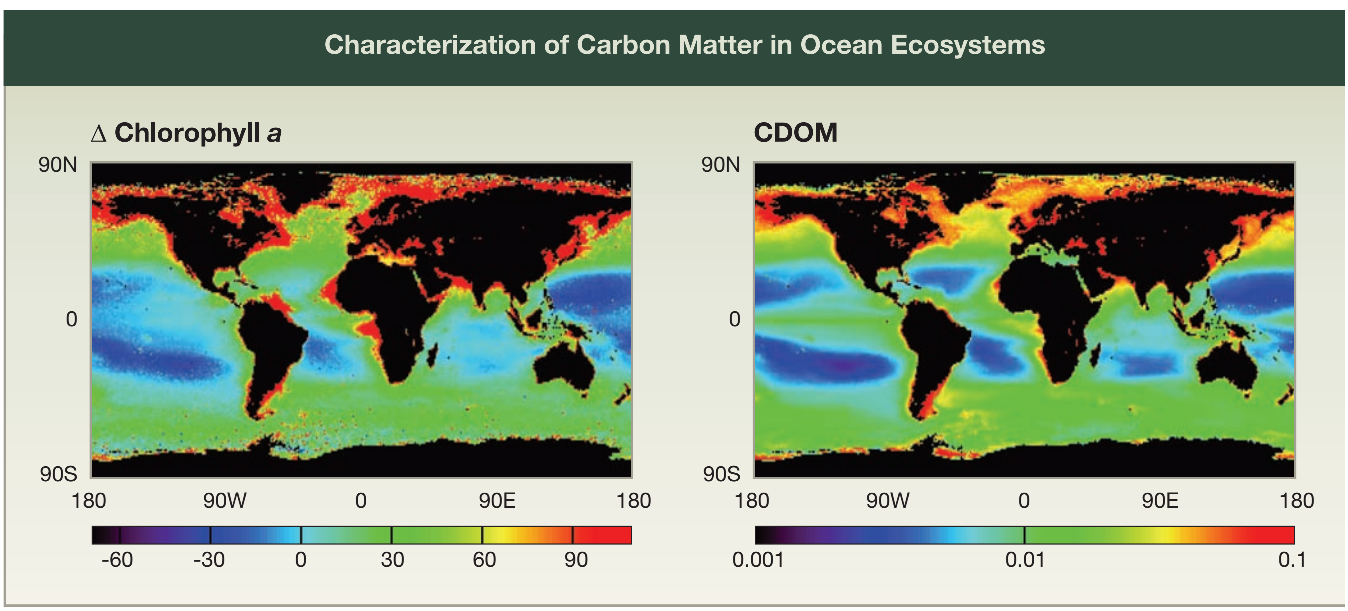
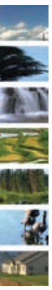


Figure 35: Characterization of Carbon Matter in Ocean Ecosystems. These data compare two algorithms used to infer the global climatology. Chlorophyll *a* concentrations differ, approaching 100% at high latitudes. The right-hand panel shows the global estimate of colored dissolved organic material (CDOM). *Credit: D.A. Siegel, University of California, Santa Barbara; S. Maritorena, University of California, Santa Barbara; N.B. Nelson, University of California, Santa Barbara; M.J. Behrenfeld, Oregon State University; and C.R. McClain NASA/Goddard Space Flight Center (reproduced from* **Geophysical Research Letters** *with permission from the American Geophysical Union).*



Highlights of FY 2007 Plans

In FY 2007, integrating observations, measurements, and models of the atmospheric, terrestrial, and oceanic components of the carbon cycle is the core research needed to quantify carbon budgets at multiple spatial and temporal scales, develop successful carbon management strategies, and reduce the uncertainties in quantifying carbon cycle dynamics. The integrated approach will include quantification of landscape-scale carbon dynamics, intensive terrestrial measurement campaigns and experimental studies, atmospheric monitoring networks, global ocean carbon surveys and inventory, coastal ocean and atmospheric carbon exchange measurements, long-term studies identifying and quantifying phenomena and processes critical to reducing uncertainties and improving predictions of future carbon dynamics, coupled carbon-climate modeling, data assimilation, and model comparisons. In 2007, carbon fluxes will be determined by "top down" (atmospheric composition and inverse transport model) techniques and, for the first time, compared and integrated with "bottom up" (land-based experiments, inventories, and monitoring networks) estimates:

- *Improved Modeling for Projections of Carbon and Climate*. New investments will be made in synthesis and modeling studies to support the NACP, the Mid-Continent NACP Intensive Campaign, the OCCC Program, global carbon dynamics, and climate change assessment activities.
- *Couple Models of the Carbon Cycle and the Climate System*. New studies will be initiated to couple models of the carbon cycle and the climate system and to analyze these models to identify, quantify, and understand process controls and feedbacks within the coupled systems. This next step in carbon cycle research responds directly to the CCSP plan for a 2- to 4-year milestone, product, and payoff of "interactive global climate-carbon cycle models that explore the links and feedbacks between the physical and biogeochemical systems." This research will be conducted in close coordination with the climate variability and change research element.
- *Carbon Data Assimilation*. New research will be conducted to develop, test, and apply carbon data assimilation and data fusion schemes that incorporate *in situ* and remotely sensed data and focus on enabling forecasts of changes in atmospheric CO_2 concentrations at short or long time scales with estimates of uncertainty. Studies to explore assimilation of carbon data from ocean margins into general circulation models will be initiated.

These activities will address Questions 7.1, 7.2, 7.3, and 7.6 of the CCSP Strategic Plan.

Terrestrial Carbon Observations and Monitoring Networks. The following research will continue to address NACP implementation strategies and other carbon cycle science goals:

- *Scaling Carbon Fluxes from Sites to Landscapes to Regions*. Carbon dioxide data from AmeriFlux sites will be extended across landscapes and regions based on turbulent transport theories using land-cover information derived from fine-resolution satellites. Several such studies will focus on landscapes throughout the United States. Some studies will extend these analyses to larger scales combining regional data from the MODIS sensor with measurements from many other AmeriFlux sites. Results from these new studies will be compared to estimates of fluxes based on biogeochemical models and, for some sites, concentration profiles of atmospheric carbon measured using tethered-sonde balloons or aircraft. The latter comparisons will be used to estimate the uncertainties involved in scaling.
- *Regional Carbon Monitoring*. A carbon atmospheric observing system will continue across the Nation in support of research to reduce uncertainty in U.S. carbon sources and sinks. The current system now includes 19 aircraft sites, *in situ* instruments at three tall towers, and seven surface flask sampling sites. The sampling, analysis, and data management activities are complemented with a growing modeling capability to aid in positioning new sites as well as in interpreting the increased flow of data. The global sampling and analytical network will continue as the cornerstone of international efforts to maintain a record of, and understand the global changes in, atmospheric CO_2 concentration and distribution over the past 50 years. The network is a critical component of the Global Climate Observing System. The program will provide critical data for analysis of regional carbon sources and sinks and useful decision-support information for carbon management.
- *Landscape-Scale Carbon Sources and Sinks in Various Ecosystem Types*. An improved observation and monitoring system that integrates several existing programs will continue at several forest sites in the United States. Standardized estimates of carbon stocks and flows will provide a strong scientific foundation for development and deployment of carbon sequestration technology to mitigate greenhouse gas emissions. Enhancing observations at experimental forests has additional benefits such as facilitating use of these sites for carbon management research and demonstration projects, and providing the basis for an "early warning" capability to detect the initial impacts of climate change. On rangelands, the recently developed National Carbon Map will be used to identify and quantify the effects of fire, grazing, and other natural disturbances and human activities on the status and trends of carbon

stocks and fluxes. The results will delineate better the spatial and temporal dimensions of current U.S. carbon sources and sinks.

- *Continental-Scale Satellite Data Time Series*. Continuing investments will be made to improve and temporally extend the continental-scale Earth Observing System satellite data products used for spatial extrapolation of carbon stock and flux estimates. In addition, these data products on primary productivity, land cover, vegetation, and phytoplankton properties of the Earth's lands and oceans will be used to drive carbon and climate models.
- *Carbon and Water Processes in the Earth System*. The Biocomplexity in the Environment initiative will continue to define and quantify key mechanisms, feedbacks, and interactions of the carbon cycle through empirical observations, theory, and modeling at the level of continents, ocean basins, and air masses. In early 2007, researchers will begin addressing carbon processes at a variety of spatial and temporal scales, and address how results can be scaled up for relevance to regional or global scales. Critical feedbacks, couplings, and interactions between the carbon and water cycles will also be addressed.

These activities will address Questions 7.1, 7.2, 7.3, and 7.6 of the CCSP Strategic Plan.

Terrestrial Field Studies: Processes, Synthesis, and Integration. Long-term field experiments and major campaigns will continue to identify processes that are critical to reducing uncertainties in carbon budgets and improving model-based predictions of future terrestrial carbon dynamics. Several scientific syntheses are anticipated in FY 2007:

- *Mid-Continent NACP Intensive Campaign*. An intensive field investigation centered on the mid-continent region of North America will continue to develop and test methods for regional and continental estimates of carbon sources and sinks through 2007. When the field studies are completed, investigators will evaluate and compare two independent approaches for estimating carbon fluxes at the regional scale: the "top down" approach using atmospheric measurements and inverse models, and the "bottom up" approach using vegetation and soil carbon inventories, land cover, meteorological information, and models. This prototype study will integrate existing data on crop, forest, and soil carbon content with data from the AmeriFlux network, airborne sensors, and satellites. Biological process information from current experiments, atmospheric profiling, and statistical databases of the mid-continent region will play key roles in the analysis. Results will contribute to the design of more comprehensive research for quantifying and explaining variation of carbon sources and sinks across North America.
- *Analysis of Regional- and Continental-Scale Carbon Budgets*. NACP studies will continue to focus on using remote-sensing observations, state-of-the-art carbon models, and data assimilation schemes to conduct integrated analysis of regional-

and continental-scale carbon budgets. These studies will bring U.S. capabilities for Earth observation, the remote measurement of biophysical properties, and related modeling, analysis, and data management to bear on NACP and related OCCC objectives.

- *Free-Air CO_2 Enrichment (FACE) Studies*. A synthesis of CO_2 exchange and belowground research at FACE sites will continue to create a data archive of photosynthesis, stomatal conductance, soil carbon and nitrogen pools, surface soil CO_2 efflux, nitrogen cycling, microbial activity, and essential metadata. Integration of field data will occur through modeling of photosynthesis and soil nitrogen cycling. This integration will be used to calibrate prognostic models of ecosystem net primary production under elevated CO_2 in nitrogen-limited and nitrogen-replete systems (i.e., under future scenarios of atmospheric nitrogen deposition).
- *Amazonian Carbon Balance*. A synthesis of carbon dynamics in the Amazon region of South America will be completed, including an assessment of the region's overall role as a source or sink of carbon and a quantification of the associated uncertainties.
- *Carbon and Water Balances in Managed Ecosystems in China and the United States*. The U.S.-China Carbon Consortium (USCCC) was established in 2003 as a collaborative effort between American and Chinese institutions studying the role of managed ecosystems in the global carbon and water cycles. The USCCC is developing a network of eddy-covariance flux towers to measure directly and continuously the net ecosystem exchange of CO_2 and water using standardized data collection, analysis, and reporting methods, and will synthesize results across sites. Planned work will focus on site installation, data protocol standardization, and initial data collection
- *Tracking Permafrost Melting and Associated Release of Biologic and Sequestered Carbon*. Ongoing research on carbon dynamics in Arctic and subarctic landscapes will be enhanced through integration with regional monitoring to assess the sources and sinks of carbon in rapidly thawing permafrost terrain. Carbon movement, including vertical flux to the atmosphere, lateral export to surface waters and the ocean, and descending transport to and re-sequestration in deeper soils, will be assessed in an integrated manner by using the Yukon River Basin and adjacent coastal ocean as a

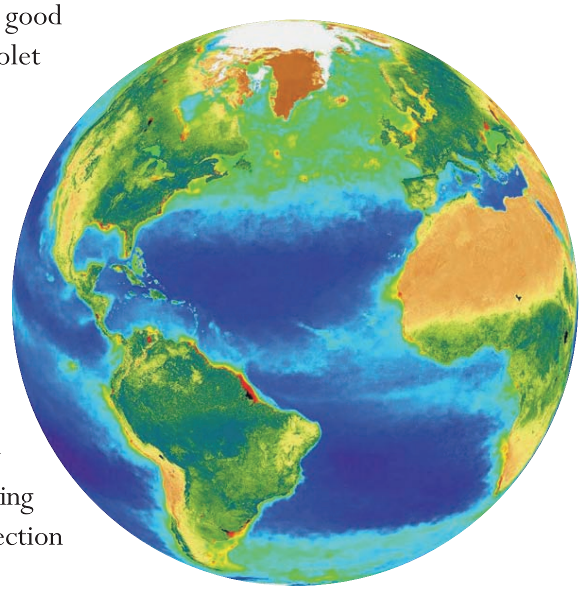
frame of reference. This assessment will begin in 2007 during the initial year of the International Polar Year.

- *Determining Carbon Sequestration Capacity in Wetlands*. Methods for greenhouse gas mitigation through terrestrial carbon sequestration are being developed that will also meet traditional wildlife habitat and ecosystem objectives in bottomland hardwood forests of the Lower Mississippi River Valley and prairie pothole wetlands in North Dakota. Wetland restoration activities will continue to be monitored to quantify the influence of land-use change on greenhouse gas emissions, identify environmental factors controlling carbon emissions and sequestration, and provide recommendations and decision-support tools for maximizing sequestration in ways that are consistent with current options for habitat restoration.

These activities will address Questions 7.1, 7.2, 7.3, 7.4, 7.5, and 7.6 of the CCSP Strategic Plan.

Ocean Carbon and Climate Change Research. New studies will be initiated, and existing studies will be strengthened, to advance the goals of the OCCC implementation strategy:

- *Refine Satellite-Based Global Estimates of Phytoplankton Carbon Biomass*. Phytoplankton biomass, specifically carbon-based estimates within biogeochemical and ecological models, is dependent on resolving CDOM absorption of the ultraviolet part of the spectrum. To accomplish this task, new measurement capabilities for the generally riverine-delivered CDOM will be developed to detect and quantify CDOM from space over a broad spatial area and within a time frame that will support models in development. One problem that will be addressed in the semi-analytical model approach is that atmospheric correction algorithms do not give good retrievals of the important ultraviolet and near-ultraviolet wavebands in coastal regions. To resolve true carbon cycling in not only global but also coastal areas, researchers need new tools in orbit to rigorously separate chlorophyll *a* from CDOM. This will require passive measurements in different wavelength regions as well as new approaches to correcting for absorbing aerosols, perhaps using Light Detection and Ranging (LiDAR) technology.



- *Satellite Data Analysis*. Studies will continue to focus on using ocean color to characterize carbon dynamics globally and on using a variety of satellite and *in situ* data to quantify and understand the spatial variability of air-sea CO_2 flux in the oceans adjacent to North America. Other studies will focus on the development and analysis of remote-sensing data and products that facilitate understanding of the input of non-CO_2, climate-relevant carbon compounds (e.g., dissolved organic matter, carbon monoxide, and CH_4) to the aquatic environment and their fate once there.
- *Dynamics of Carbon Cycling in the Upper Ocean*. The two time-series stations at Hawaii and Bermuda will continue to monitor a suite of critical parameters of the carbon cycle while also supporting a range of carbon-related projects such as nitrogen fixation by unicellular cyanobacteria and phosphorus cycling that determines the amount of carbon fixation. Focused process studies will be completed to better define the role of mesoscale eddies in enhancing new production and the transport of particles from the upper ocean to the deep sea.

- *Ocean Hydrography and Carbon Measurements*. The Repeat Hydrography Program will continue to re-measure key ocean properties along cross-sections in the South Atlantic and North Pacific that were last measured in 1989 and 1991, respectively. The suite of measurements will include conductivity, temperature, depth, oxygen, salinity, nutrients, partial pressure of CO_2, and total carbon.

These activities will address Questions 7.1, 7.2, and 7.4 of the CCSP Strategic Plan.

Development of New Measurement and Analysis Methods. The following activities will be underway to develop new measurement standards and data analysis methodologies for carbon cycle science:

- *Carbon Dioxide Exchange Across the Air-Sea Interface*. New gas sensors will be designed specifically for use on autonomous platforms such as floats, gliders, surface drifters, and autonomous underwater vehicles. The objective is to develop parameterizations for gas exchange rates at high wind speeds, where the largest uncertainties remain for computing net global CO_2 exchange between the ocean and the atmosphere. Modeling and data analysis will focus on understanding the physics of bubble-mediated gas transfer, particularly the processes responsible for gas influx and efflux, the roles of bubble size, and the relationships between wind, waves, bubble generation, ocean turbulence, and vertical exchange.
- *Satellite Measurements of Atmospheric Carbon Dioxide*. Development of the new remote-sensing capabilities of the Orbiting Carbon Observatory (OCO) to measure atmospheric CO_2 will continue. In 2007, the ground data system for OCO will be tested and research will be conducted to prepare for scientific data utilization.

Globally sampled measurements of atmospheric column CO_2 (i.e., the column-integrated CO_2 dry air mole fraction) will provide a hundred-fold increase in the available measurements to drive inverse models and should enable regional resolution of carbon sources and sinks. Launch of the OCO is scheduled for 2008.

- *AmeriFlux Data Assimilation System*. An integrated framework for using AmeriFlux measurements and ecosystem models will continue to improve understanding of terrestrial carbon cycling processes. This framework, called the AmeriFlux Data Assimilation System, takes advantage of diverse, continuous AmeriFlux measurements of CO_2 and energy exchanges, and combines them with a detailed process-based ecosystem model. It will yield information on ecosystem states and carbon sinks in real-time and will be an effective tool for scientists to investigate fundamental ecological processes that are difficult to observe directly.

These activities will address Questions 7.1, 7.2, 7.4, and 7.5 of the CCSP Strategic Plan.

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6 | Ecosystems

Strategic Research Questions

8.1 What are the most important feedbacks between ecological systems and global change (especially climate), and what are their quantitative relationships?
8.2 What are the potential consequences of global change for ecological systems?
8.3. What are the options for sustaining and improving ecological systems and related goods and services, given projected global changes?

See Chapter 8 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of these research questions.

Ecosystems provide goods (e.g., food, fiber, fuel, pharmaceutical products) and services (e.g., the cycling of water and nutrients, the regulation of weather and climate, the removal of waste products, natural beauty, sustaining biological diversity) to society. Global change—including land-use change and climate change, as well as other environmental change such as habitat fragmentation, the spread of invasive species, and pollution—is affecting the ability of these life support systems to sustain the goods and services required by our growing population. Therefore, it is important to focus research on furthering our understanding of ecosystem processes, including the interactions of ecosystems with the atmosphere and physical climate system as well as the effects of human activities on ecosystems. The goal of the ecosystems research element is to understand and project the potential effects of global change on ecosystems, the goods and services ecosystems provide, and ecosystem links to the climate system. This improved understanding leads to better management practices because of the ability to anticipate longer term ecosystem effects.

In FY 2007, one research focus for the CCSP Ecosystems Interagency Working Group (EIWG) is to increase understanding of the relationship between climate variability and change and ecosystem net primary production and biodiversity. Topics of emphasis are societally important ecosystems and regions where near-term abrupt environmental changes may occur. A central element of this effort will be the ongoing development and improvement of predictive models that operate across spatial scales to enable ecological forecasting for aquatic and terrestrial ecosystems. Research conducted by CCSP member agencies continues to improve our understanding of the drivers and impacts of climate variability and change. The challenge for the EIWG lies in furthering our understanding of the relationship of these drivers and impacts to ecological processes, which will ultimately require the linking, if not direct coupling, of geophysical climate models with ecosystem models.

This EIWG effort contributes to all five CCSP Goals with an emphasis on Goal 4. It also directly addresses the CCSP ecosystems research element questions 8.1, 8.2, and 8.3. Strong synergies and interactions exist with other CCSP research elements, including, but not limited to, the climate variability and change, water cycle, carbon cycle, and land-use/land-cover change research elements.

Successful research and application require collaboration across agencies, as well as ongoing input from scientists within and outside the Federal government. The participating agencies of the EIWG work collaboratively in research program oversight and execution as described in the *CCSP Strategic Plan*. Many of the research accomplishments and plans described in this chapter represent the joint efforts of multiple agencies and/or the work of agencies and their external partners and cooperators. The EIWG engages the research community in providing input and feedback on its plans.

HIGHLIGHTS OF RECENT ACTIVITIES

Priority Setting for Ecosystems Research in CCSP Workshop Report.[10] A non-Federal writing team has published *Ecosystems and Climate Change: Research Priorities for the U.S. Climate Change Science Program: Recommendations from the Scientific Community*, a report of the EIWG workshop held in 2004. More than 70 scientists came together in the workshop to identify and discuss priorities and approaches for the Ecosystems chapter (Chapter 8) of the *CCSP Strategic Plan*. The authors used the presentations and breakout summaries to develop recommendations and insights for the EIWG to use in program development. The report concludes that Chapter 8 in the *CCSP Strategic Plan* provides a good foundation and establishes boundary conditions for ecosystems research. General themes included the need to improve observation systems; use more large-scale experiments; integrate models using monitoring data, observations, and experimental data; and communicate results and uncertainties to policymakers and resource managers. A central recurring theme was the need to develop better mechanistic understandings of ecosystem processes, including interactions of ecosystems with the atmosphere, climate, and human activities, to better model and increase our confidence in predictions of ecosystem responses and feedbacks to global changes.

Positive Feedback Effect of Arctic Warming: Shrub and Tree Expansion into Snow-Free Areas.[4] As concentrations of greenhouse gases in the atmosphere increase, a major challenge to predicting Earth's future climate is understanding how various feedbacks alter the contribution of greenhouse gases to climate change. Synthetic analysis of field data collected in arctic Alaska show that summer changes in the reflectivity (albedo) of arctic terrestrial environments contribute substantially to observed recent warming in the Arctic. Specifically, recent pronounced terrestrial summer warming in arctic Alaska correlates with a lengthening of the snow-free season, amplifying global warming in the Arctic through a positive feedback mechanism involving reduced snow cover (highly reflective)—the main cause of summer warming observed to date—and expanding shrub and tree cover, which is likely to contribute disproportionately to future summer warming. As a result, atmospheric heating has increased by approximately 3 Wm^{-2} per decade—a value similar to the regional heating expected over multiple decades from a doubling of atmospheric CO_2. Calculations show that 11,600 km^2 has been converted from tundra to forest in the last 50 years, representing 2.3% of the Arctic's treeless area. Current general circulation models include the positive feedbacks of reduced snow cover on global warming, but not the additional feedbacks caused by changes in vegetation, which could raise seasonal temperatures by an additional 1.1 to 1.6°C (see Figure 36).

Productive Forests May Respond Most Rapidly to Global Change.[14] Forests provide humans with irreplaceable goods and services and sequester the majority of the terrestrial biosphere's carbon, making them key components of the global carbon cycle. Trees in the world's most productive forests—forests that add the most new growth each year—tend to die at a younger age than trees in less productive forests. This discovery, based on a compilation and analysis of results from hundreds of long-term studies worldwide, could help scientists predict how forests will respond to ongoing and future environmental changes. Recent analyses of these data demonstrated that forest turnover rates (birth and death rates of trees) vary directly in parallel with global and regional patterns of forest productivity. Half of all trees in tropical forests growing on rich soils die and are replaced by new trees in just 30 years. In comparison,

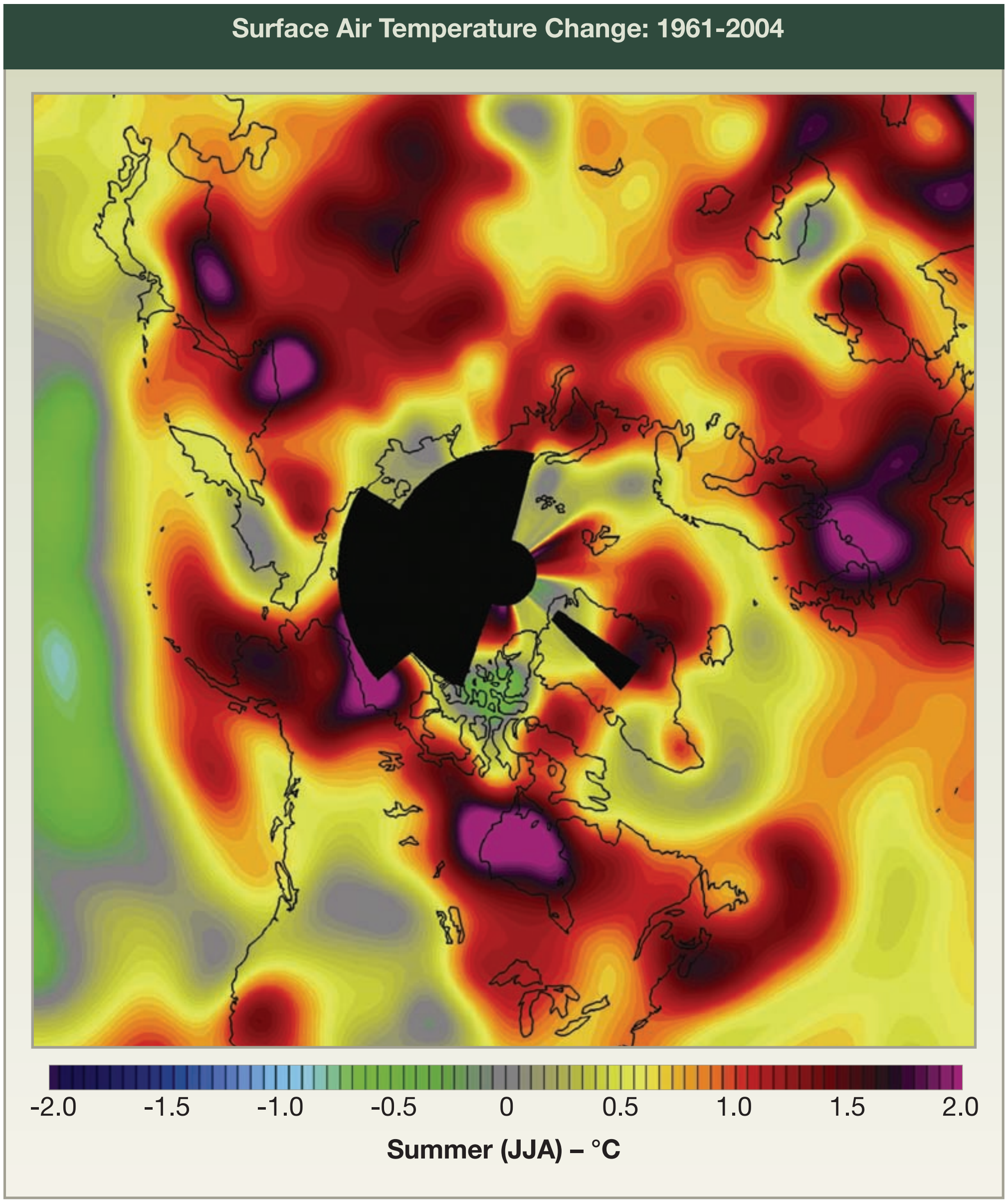


Figure 36: Surface Air Temperature Change: 1961-2004. This product provides the spatial pattern of high-latitude summer (June to August) surface warming (in °C over 44 years, 1961 to 2004). The pattern of temperature increase was estimated from monthly anomalies of surface air temperature from land and sea stations throughout the Northern Hemisphere, updated from Chapman and Walsh (1993). *Credit: F.S. Chapin, III, University of Alaska–Fairbanks (reproduced with permission from* **Science***).*

a century or more can pass before half of the trees die and are replaced in coniferous forests growing at high latitudes. Implications of more rapid turnover in tree populations include: 1) The world's most productive forests may be those that are likely to respond most quickly to future environmental changes such as climate change; 2) environmental changes that increase the productivity of a given forest could also lead to more rapid turnover of trees, decreasing the average age of trees in that forest; 3) other environmental changes that increase forest productivity (e.g., nitrogen deposition) may also increase forest turnover rates, leading to forests that are more heavily dominated by younger and smaller trees, with potential effects on wildlife and biodiversity; 4) managers wishing to establish forest-monitoring programs for change detection may wish to devote extra effort toward monitoring their most productive forest types; and 5) increased dominance by younger trees could lead to changes in the amount of carbon sequestered or stored by forests. Given the central importance of forests to the global carbon cycle (hence also to global climate change), and the increasing importance of carbon storage to international treaties and trading of carbon credits, it is important to develop a solid understanding of the relationships among forest productivity, turnover, and carbon storage. This study is among the first to shed light on these relationships.

Invasive Species Alter Ecosystem Biogeochemistry in Hawaii Volcanoes National Park.[1] Using imagery from the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) sensor, researchers at the Carnegie Institution and Stanford University have documented the impacts of two invasive species, the nitrogen-fixing tree *Myrica faya* and the understory herb *Hedychium gardnerianum*, on the water content and nitrogen balance in the montane rain forest of Hawaii Volcanoes National Park. These impacts leave a spectral signal at the top of the tree canopy, which is detectable by AVIRIS. The park landscape is young, and the low nitrogen content of its volcanic soils limits forest productivity, leaving a native *Metrosideros polymorpha* forest canopy that is low in nitrogen and water content.

The invasive species are driving fundamental changes in ecosystem properties. *Myrica faya* fixes nitrogen from the atmosphere, a capacity the native trees lack. Its canopy is high in nitrogen, and has higher water content. Higher ecosystem nitrogen concentrations have led to faster leaf turnover, higher rates of nutrient cycling, faster decomposition, greater nitrogen availability, greater fluxes of nitrogen-containing trace gases, and ultimately invasion by other nutrient-demanding species. While the impacts of the tree *Myrica faya* occur at the canopy level and thus allow direct detection by remote-sensing systems, locating the understory herb *Hedychium gardnerianum* within the heavy forest is also possible due to its significant effects on nitrogen and water levels in the canopy vegetation above it. Classification of the entire park area based on canopy chemistry shows that *Myrica* now dominates 28% of the landscape and an additional 23% is undergoing transformation, with *Myrica* growing into the canopy. Up to 13% of the remaining native forest is infested with *Hedychium*. The canopy nitrogen content of the entire region has doubled as a result of the invasion of *Myrica*, while the effects of *Hedychium* are only beginning to be investigated. Park managers are using the results from this initial study for planning and control of invasive species. The researchers are also trying to expand the study to include additional invasive species that maintain unique biochemical properties observable from imaging spectroscopy. This work documents the ability of invasive species to alter ecosystems in fundamental ways by not only changing the composition and relative abundance of species but also by dramatically affecting how these systems cycle water and elements vital for life.

Wood Compression Strength Loss as an Index of Organic Matter Decomposition in Boreal Forest Mineral Soil.[7] Organic matter decomposition is used in climate change models to assess the possible impacts of temperature increases on soil carbon in high-latitude (>50°N) boreal forests. Decomposition studies in this region have mostly focused on surface litter, but very few have investigated organic matter decomposition in mineral soil as a function of different climates. A 3-year field study in six Scots pine plantations along a north-south temperature gradient from Finland to Poland showed that radial compression strength loss was a good index of wood decomposition. Compression strength losses in wood stakes ranged from 20% in northern Finland to 94% in central Poland, which corresponded to dry weight reductions of 3 and 65%, respectively. The compression strength test was a more sensitive indicator of wood decomposition in colder Finnish soils, which had no stake weight loss at most soil depths after 3 years. Both compression strength loss and weight loss decreased as soil depth increased, which likely reflect lower mineral soil temperatures. Chemical analysis of the wood stakes showed a progressive proportional decrease in lignin, cellulose, and hemicellulose content with total weight and carbon loss. In contrast, wood nitrogen concentration and content increased as decay progressed. Results of these studies in Europe indicate that wood stakes can be used to measure organic matter decomposition in mineral soil across a range of climate conditions or as climate changes.

Integrating the Effects of Land Use and Global Climate Change on Hydrology and Vegetation of Northern Great Plains Wetlands.[6] The Prairie Pothole Region (PPR) in central North America contains millions of glacially formed, depressional wetlands embedded in a matrix of native grassland and agriculture (see Figure 37). These wetlands provide valuable ecosystem services to human populations, and represent the single most productive habitat for waterfowl in the world. Wetland availability and emergent cover conditions are the primary factors that

Figure 37: The Prairie Pothole Region. This photograph provides an aerial view of glacially formed, depressional wetlands embedded in a matrix of native grassland and agriculture, located in the Prairie Pothole Region of central North America. Recent research based on possible future climate scenarios suggests that these wetlands and their ability to support breeding waterfowl will be altered. *Credit: J. Ringleman, Ducks Unlimited.*

determine the number and diversity of breeding waterfowl that will settle in the PPR. The well-established sensitivity of prairie wetlands to climate variability portends a similarly sensitive response to future climate change. Climatic fluctuations drive hydrology that in turn drives key processes in prairie wetlands. This project was initiated to quantify how these wetland systems respond to climatic oscillations at regional scales and to develop simulation models to forecast wetland responses to future climatic change. The broad spatial and temporal responses across the PPR in terms of climate, wetland water levels, and vegetation were explored by applying a wetland simulation model. Model simulations suggest that the most productive habitat for breeding waterfowl would shift under a drier climate from the historic center of the PPR in the Dakotas and southeastern Saskatchewan to the wetter eastern and northern fringes, areas that are currently less productive or where the majority of wetlands have been drained. Based on these results, unless wetlands in these fringe areas of the PPR are protected and restored, there is little insurance for waterfowl in the region if faced with future climate warming. Results suggest a significant shift in the efforts of wetland managers and where future restoration dollars should be spent in an uncertain climate future.

Rising Atmospheric Carbon Dioxide May Alter Rangeland Quality.[12,15] Rangelands are an important managed ecosystem in North America, providing food and fiber to large animal populations. Long-term results from the USDA Rangeland Resource Unit indicate that although rising atmospheric CO_2 can enhance forage

production of shortgrass prairie, it results in lower quality forage that can degrade animal performance. Cheatgrass is a recognized invasive annual weed of ecosystems in the western United States that reduces fire return times from decades to less than 5 years. Results from the USDA Crop Systems and Global Change Unit indicate that increases in atmospheric CO_2 during the 20th century have been sufficient to increase aboveground biomass of this invasive species by 1.5 to 2.7 g per plant for every 10 parts per million (ppm) increase in CO_2 above the 270-ppm pre-industrial baseline. These data suggest that increasing atmospheric CO_2 may have contributed significantly to cheatgrass productivity and fuel load with subsequent effects on fire frequency and intensity.

Warming May be Causing Decline of Biological Soil Crusts in Semi-Arid Ecosystems.[3] Drylands, including deserts, shrublands, savannas, and woodlands, represent about 35% of U.S. land area. Biological soil crusts are the dominant living soil cover in many of these ecosystems, and are critical for nitrogen (through atmospheric molecular nitrogen assimilation) and carbon inputs to soils. These inputs support soil food webs and the mineral nutrition of vascular plants. Biological crusts also contribute to soil stability (reducing erosion) and water infiltration, and provide important local environments for seed germination. Monitoring in a semi-arid grassland in Utah that

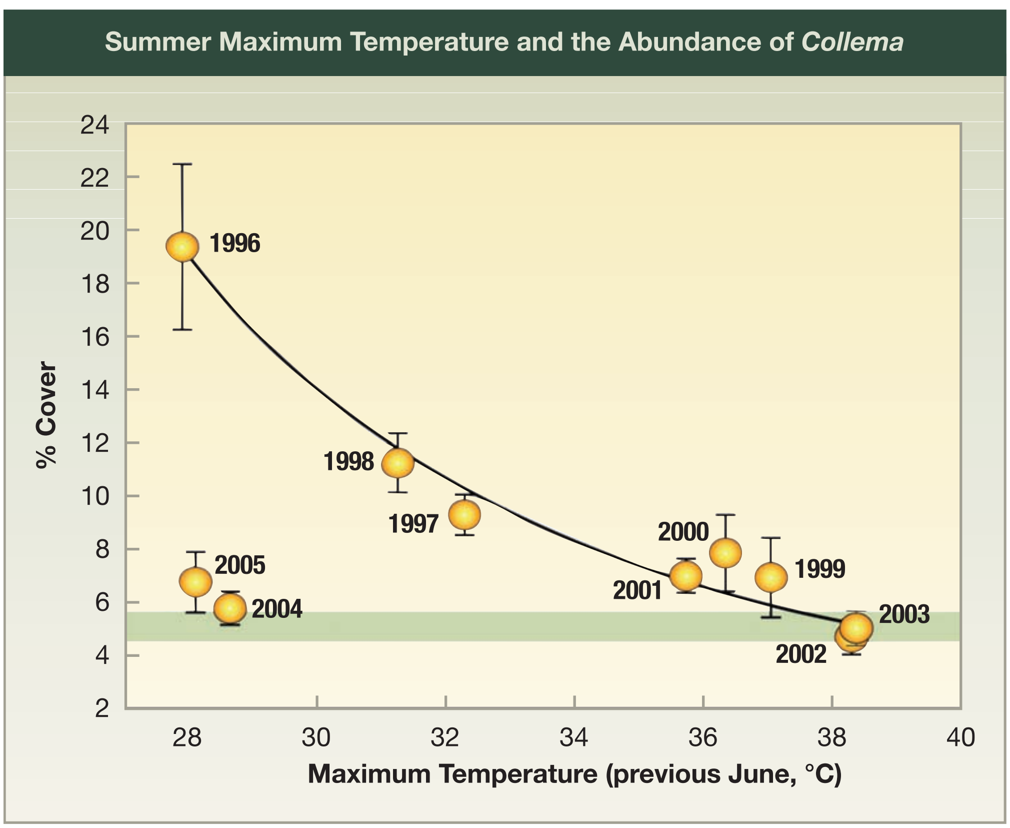


Figure 38: Summer Maximum Temperature and the Abundance of *Collema*. A negative correlation existed between summer maximum temperature (mean daily maximum temperature during June) and subsequent abundance of the lichen *Collema*, which dominates the biological soil crust in many semi-arid western ecosystems. Even after 2 cooler years, the lichen had not recovered from the warm period of 1997 to 2003. *Credit: J. Belnap, S.L. Phillips, and T.T. Troxler, U.S. Geological Survey.*

is protected from human disturbance indicates that the dominant lichen in the soil crust, *Collema*, was detrimentally affected by the unusually warm summers between 1996 and 2003 (see Figure 38). The cooler summers of 2004 and 2005 produced limited recovery of *Collema* populations. These results indicate that warming in the arid and semi-arid west has the potential to rapidly alter the abundance of ecologically important organisms. This observation is being tested by experimentally warming field plots and quantifying the effects on plant communities and the biological soil crusts supporting them.

Rising Atmospheric Carbon Dioxide Concentration May Counteract Detrimental Effects of Increased Ozone Pollution on Tree Growth.[8,9] Research at the DOE Free-Air CO_2 Enrichment (FACE) facility near Rhinelander, Wisconsin, is determining possible effects of rising concentrations of CO_2 and ozone (O_3) in the lower atmosphere on the growth (accumulated living biomass) of northern hardwood tree stands. After 6 years of treatments using concentrations of O_3 projected for the year 2050 (i.e., 50% greater than today), total biomass of aspen stands, aspen-birch mixtures, and aspen-maple mixtures was reduced by 23, 13, and 14%, respectively. However, when the elevated O_3 treatment was combined with the CO_2 concentration projected for the year 2050 (i.e., 560 ppm), the aspen biomass was only 8% lower compared to stands growing in the present ambient atmosphere. Moreover, the accumulated biomass of the aspen-birch and aspen-maple mixtures was stimulated (8 and 24%, respectively) by the combination of elevated CO_2 and elevated O_3 relative to the present ambient atmosphere. The results emphasize the importance of studying multiple changes in the environment rather than single (isolated) factors only, and indicate the importance of species-specific effects of environmental change.

Transfer of Carbon to Adjacent Aquatic Ecosystems in Enhanced Carbon Dioxide Studies.[11] Carbon export from wetlands to estuaries is quantitatively important at ambient CO_2 levels. Study results suggest that elevated atmospheric CO_2 concentrations may increase carbon export from some tidal marshes to estuaries. In a long-term tidal marsh experiment, elevated CO_2 increased soil-water concentrations of dissolved inorganic carbon by 27% at 30-cm depth. The elevated CO_2 treatment also increased concentrations of dissolved organic carbon and methane, but by less significant amounts (15 to 27% and 12 to 18%, respectively). This is important because the export of

inorganic and organic carbon from tidal marsh soils affects the chemistry and productivity of adjacent estuaries. The study is among the first to suggest that elevated CO_2-enhanced metabolism in terrestrial systems may indirectly influence water quality and metabolism in adjacent aquatic ecosystems.

Impacts of Climate Change on the Success of Watershed-Scale Restoration Strategies in Puget Sound.[2,13] Landscape-scale watershed planning efforts aimed at restoring the structure and function of river basins are ubiquitous across the country. Motivations for these restoration efforts typically include maintaining and improving water flows and water quality and recovering imperiled species. This project involved developing models of climate impacts in the western United States, where considerable resources have been devoted to designing large-scale habitat restoration plans to bolster water quantity and promote recovery of salmon and other aquatic species. Most models predicting the ecological outcomes of such restoration plans do not include the potential effects of multiple environmental changes in forecasting possible outcomes. In particular, future climate is likely to affect several important determinants of habitat quality and quantity, including seasonal flow rates and water temperature. A loosely linked system of process-based models of climate, hydrology, and salmon population dynamics was used to examine the possible effects of climate change over the next 50 years on freshwater habitat conditions in the Snohomish River Basin in western Washington.

The project also explored how predicted impacts of habitat restoration strategies on salmon are likely to differ when climate change impacts on habitat are included in predictions of future chinook salmon response. Meteorological output from two global climate models was downscaled and used to drive a streamflow and temperature model, the output of which was used to drive a salmon life cycle model. Model results suggest that climate change will cause increased winter peak streamflow, decreased summer flow, and increased water temperature throughout the year, all of which are likely to have negative effects on salmon survival and reproduction. The two climate models used in the study project different seasonal patterns of rainfall, which has a large impact on the magnitude of predicted salmon population declines, suggesting a substantial degree of inherent unpredictability in the projection of climate change effects on freshwater systems. Model projections suggest that climate change in this basin may cause 14 to 38% declines in salmon populations. The concurrent changes in stream habitats due to planned habitat and land-use restoration actions are likely to lessen the salmon declines, but meeting population recovery targets adopted for salmon, and water quantity demands for agricultural, urban, and other rural uses, is likely to be much more difficult in the face of climate change (see Figure 39).

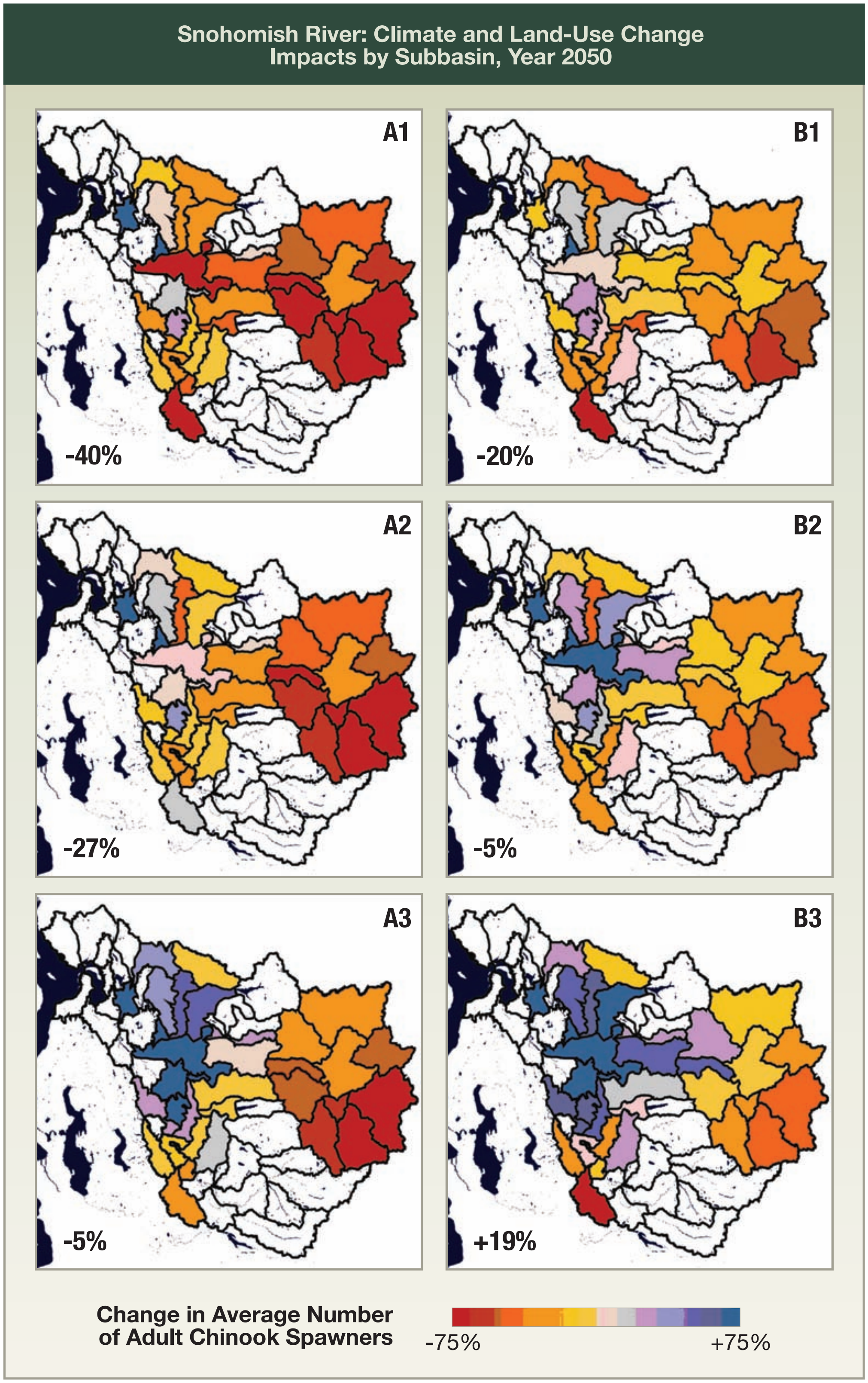
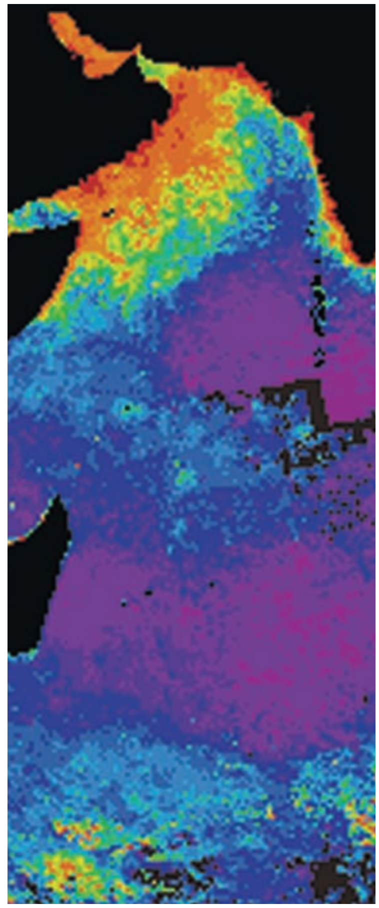


Figure 39: Snohomish River: Climate and Land-Use Change Impacts by Subbasin, Year 2050. This graphic provides the projected change in abundance of spawning Chinook salmon between 2000 and 2050 under two scenarios of future climate and three scenarios of future land use. The panels in column A are based on downscaled predictions of the GFDL_R30 climate model; column B is based on the HadCM3 climate model. Row 1 features current (2001) land use; row 2 features a scenario including a moderate amount of habitat restoration; and row 3 features a scenario in which the restoration plan for the basin is fully implemented. The number in the lower left corner of each panel indicates basin-wide total change in abundance. *Credit: M.W. Wiley, University of Washington.*

Warming of the Eurasian Landmass Making the Arabian Sea More Productive.[5] Scientists have used NASA data from ocean color satellites to show that phytoplankton concentrations in the western Arabian Sea have increased by more than 350% over the past 7 years. This increase in phytoplankton coincided with satellite observations of a decrease in snow cover in Eurasia. Since 1997, the decline in snow cover has caused a land-ocean thermal gradient that is particularly favorable to stronger southwest (summer) monsoon winds. The sea surface winds have been strengthening over the western Arabian Sea resulting in stronger monsoon winds and accompanied by enhanced upwelling. The strengthened upwelling is the source of the nutrients causing the blooms. While blooms of phytoplankton can enhance fisheries, they could be detrimental to the local ecosystems, causing eutrophication and oxygen depletion (hypoxia or anoxia) that could lead to a decline in fish populations and the production of chemically relevant trace gases such as nitrous oxide (see Figure 40).



HIGHLIGHTS OF FY 2007 PLANS

Models of Terrestrial Ecosystems. An important aspect of better understanding the relationship between ecosystems and climate change is establishing and modeling impacts and feedback. Efforts are focused on combining observations, inventory, and experimental data into ecological models coupled with regional and global climate prediction models. A number of projects focused on improving and coupling such models are part of CCSP-sponsored research efforts:

- *Mountain Ecosystems*. A landscape disturbance model will be used to predict responses of western mountain ecosystems to combinations of climate change and altered fire regimes. This approach will provide linkages between broad-scale climate variability and wildfires, and will become the basis for forecasting extreme wildfire years through empirical models using annual and decadal climate variability data.
- *Forests*. A satellite-derived vegetation index for tree species will be developed using USDA Forest Service Forest Inventory and Analysis national forest inventory data

Reversal in Wind Direction during the Southwest Monsoon

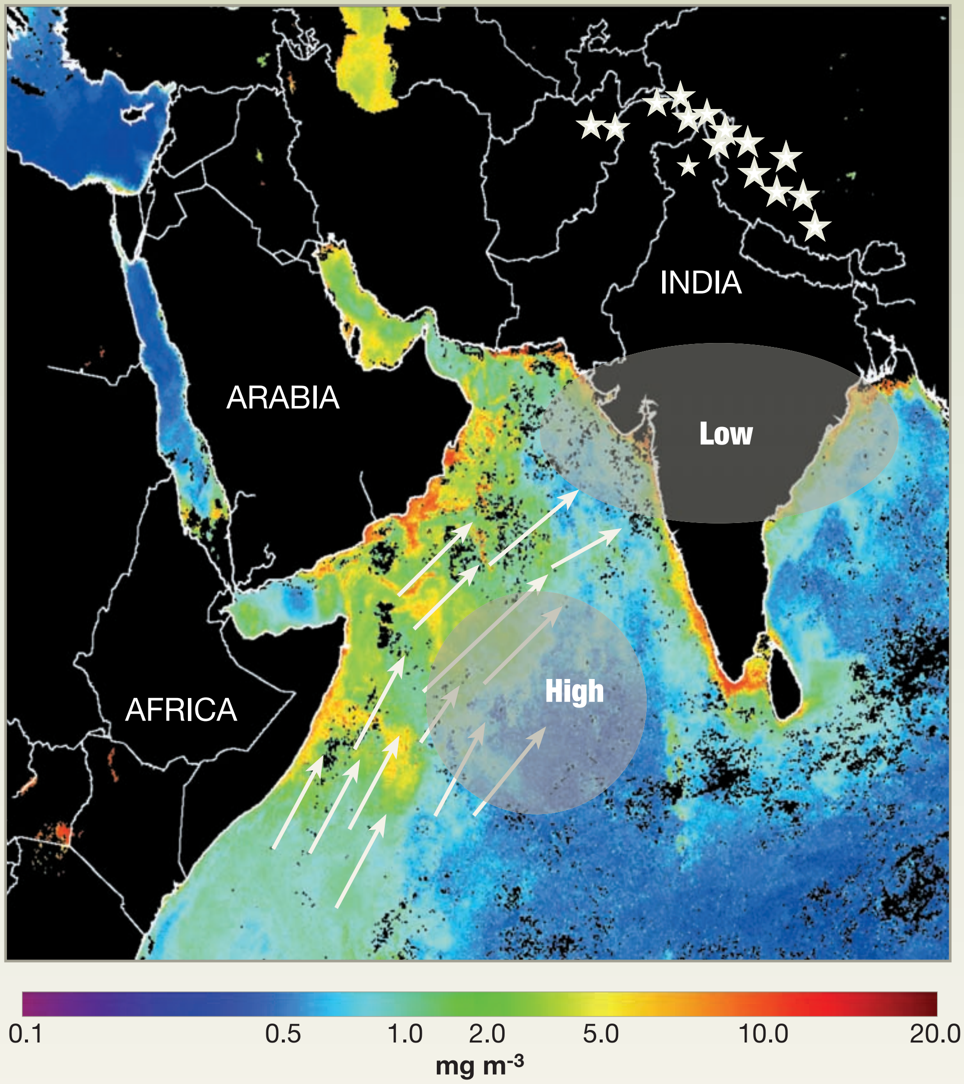


Figure 40: Reversal in Wind Direction during the Southwest Monsoon. This schematic shows the reversal in wind direction during the southwestern monsoon (June to September) resulting from changes in the land-sea pressure gradient. *Credit: J.I. Goes, Bigelow Laboratory for Ocean Sciences.*

and enhanced NASA satellite vegetation data. The study will cover 65 U.S. ecoregions and will explore the relationship between productivity and diversity at regional to national scales. Repeated surveys will provide information about the impacts of a changing climate on productivity.

- *Watersheds*. Regional assessments have shown potential impacts on water resources due to the feedbacks between land use and climate change. A review of public watersheds will provide information about current decisionmaking practices and help prioritize science needs and watersheds most likely to be affected.

These tools will improve our ability to understand and project changes in the distribution of organisms with changes in climate and other environmental factors. A number of projects on feedbacks between ecological systems and global change are closely related to feedbacks being investigated through other research elements and are being coordinated with other working groups.

These activities will address Questions 6.2, 8.1, 8.2, 8.3, and 9.2 of the CCSP Strategic Plan.

Terrestrial Ecosystem Research. Terrestrial ecosystems research priorities in FY 2007 follow:

- *Soils*. A genetic signature from soil microorganisms will be used to develop an understanding of the mechanisms that control nitrous oxide flux from soil. This knowledge will be used to better predict nitrous oxide concentrations in the atmosphere under changing precipitation resulting from different climatic conditions.
- *Long-Term Ecological Research Sites*. Long-Term Ecological Research sites provide substantial laboratories for developing an understanding of global change impacts on a variety of ecosystems. Ten sites are under review for renewal and will be evaluated for their contributions to improved understanding and management of ecosystems under a changing environment.
- *Species Invasion of Ecosystems*. The existing science related to species invasions associated with global change and their impacts on ecosystems will be evaluated. Invasive species are one of the primary threats to ecosystems and biodiversity. More information is needed to better monitor and adapt existing management practices to help reduce impacts.
- *Forest Markets and Trends*. Fifty-year projections of future regional forest markets and trends in forest conditions under alternative climate assumptions will be developed. The projections will look at modified growth rates and the geographic distribution of forests in North America. This information will be useful for policymakers concerned with the long-term implications of climate change on the Nation's forest ecosystems.
- *Food Security*. Food security requires the ability to predict accurately crop-pest relationships in a changing environment. Studies are underway to address the possible impacts of climate change and atmospheric CO_2 on pest biology. Specifically, the direct effects of CO_2 and concomitant changes in climate on weed growth and weed/crop competition, and secondary effects on crop hosts that may affect insect fecundity and pathogen success, will be evaluated.
- *Precipitation Change in Piñon-Juniper Ecosystems*. The southwestern United States is currently experiencing an extended drought, which has been blamed for widespread tree mortality. Although many coniferous species have been affected, the most extensive mortality has occurred to piñon pine (*Pinus edulis*), a species that

dominates one of the most extensive vegetation types in western North America, the piñon-juniper woodlands. Future climatic change is expected to exacerbate the frequency and severity of droughts in the southwestern United States. The first large-scale, replicated experimental study of the effects of changes in precipitation on a piñon-juniper ecosystem will be underway in FY 2007.

These activities will address Questions 8.1, 8.2, 8.3, and 9.2 of the CCSP Strategic Plan.

Aquatic Ecosystem Research. Aquatic ecosystem research priorities in FY 2007 include using integrated modeling systems, observations, and process studies to project the effects of climate variability and change on near-coastal and marine ecosystems, communities, and populations using field work, observations, and ecosystem models:

- *Phytoplankton Carbon Biomass*. Global estimates of phytoplankton carbon biomass from remote-sensing data will be used to develop carbon/chlorophyll ratios in order to couple carbon and ecosystems models, and later to couple these with climate models. The comparison between observations and models helps improve the ecological models, therefore improving the ability to predict the responses of the ocean ecosystem and carbon stocks to global warming.
- *Salmon and Other Species Response to Climate Variability*. A collaborative research program will synthesize field and model information in the northeast Pacific to better understand and predict responses of these ecosystems to climate change. This synthesis will provide information for policymakers and decisionmakers about how salmon and other similar species respond to climate variability across the regions.
- *Coral Reefs*. Research addressing several potential climate-related threats to coral reefs will be advanced. A reef calcification index will be developed to provide an important bioindicator of overall reef health, and sustained monitoring will yield important insights into the impact of ocean acidification on these delicate systems. In addition, research will continue to develop a bleaching forecast system to provide managers and researchers with advance warning of impending thermal stress.
- *Coastal Wetlands*. The effects of elevated CO_2 on coastal wetlands and interactions with sea-level rise is very complex and not well understood. Experiments at a long-running marsh site using elevated CO_2 will be used to develop relationships between plant production, decomposition, and soil carbon and nitrogen. The studies will provide important information about how tidal wetlands respond to sea-level rise.

These activities will address Questions 8.1, 8.2, and 8.3 of the CCSP Strategic Plan.

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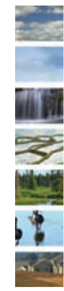


7 | Decision-Support Resources Development and Related Research on Human Contributions and Responses

CCSP Decision-Support Goals

Decision-Support Goal 1: Prepare scientific syntheses and assessments to support informed discussion of climate variability and change and associated issues by decisionmakers, stakeholders, the media, and the general public.

Decision-Support Goal 2: Develop resources to support adaptive management and planning for responding to climate variability and climate change, and transition these resources from research to operational application.

Decision-Support Goal 3: Develop and evaluate methods (scenario evaluations, integrated analyses, and alternative analytical approaches) to support climate change policymaking and demonstrate these methods with case studies.

Strategic Research Questions

9.1 What are the magnitudes, interrelationships, and significance of the primary human drivers of, and their potential impact on, global environmental change?

9.2 What are the current and potential future impacts of global environmental variability and change on human welfare, what factors influence the capacity of human societies to respond to change, and how can resilience be increased and vulnerability reduced?

9.3 How can the methods and capabilities for societal decisionmaking under conditions of complexity and uncertainty about global environmental variability and change be enhanced?

9.4 What are the potential human health effects of global environmental change, and what climate, socioeconomic, and environmental information is needed to assess the cumulative risk to health from these effects?

See Chapter 11 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of decision-support resources development and Chapter 9 for these specific research questions.

One of the main purposes of CCSP is to provide information for informed decisionmaking through the development of decision-support resources. In the context of activities within the CCSP framework, decision-support resources, systems, and activities are climate-related products or processes that directly inform or advise stakeholders in order to help them make decisions. These products or processes include analyses and assessments, interdisciplinary research, analytical methods (including scenarios and alternative analysis methodologies), model and data product development, communication, and operational services that provide timely and useful information to decisionmakers, including policymakers, resource managers, planners, government officials, and other stakeholders. Decision-support resources and activities include not only research activities based in the natural sciences, but also activities related to human contributions and responses to climate variability and change, such as demography, economics, history, anthropology, political science, and sociology.

Scientific and Stakeholder Input and Guidance

National Research Council Advice

An important source of scientific expertise and judgment on societal issues related to global change is the Committee on the Human Dimensions of Global Change (CHDGC) of the National Research Council (NRC). The committee was formed in 1989 to help guide U.S. research on the interactions between human activity and global environmental change. CHDGC focuses on two main tasks: developing the intellectual basis for progress in understanding human-environment interactions, and advising on future research directions. The committee's advice is particularly relevant to CCSP's human contributions and responses research element, as well as some aspects of the program's decision-support activities. An *ad hoc* committee has also been convened to conduct a comparative analysis of assessments related to climate change, and will produce a report that will be used to inform CCSP's future climate assessment activities (Decision-Support Goal 3). This study, *Lessons Learned from Climate and Global Change Assessments*, will attempt to identify ways to make global change assessments more useful for policy and research.

CCSP Workshop

The program's progress and future plans regarding its three decision-support goals were addressed in November 2005 at a CCSP workshop, *Climate Science in Support of Decisionmaking*, in Arlington, Virginia. Over 700 individuals participated in the workshop, including an international audience of climate scientists, decisionmakers, and users of information on climate variability and change from academia, governments at the State, local, and national levels, nongovernmental organizations, Congress, interest groups, and the private sector.

The workshop featured plenary presentations from high-level policymakers, scientists, and the private sector, and several breakout sessions conducted over a 2-day period. The first set of breakout sessions was organized to provide information to participants on the status of assessments being prepared (or recently completed) by CCSP, the Intergovernmental Panel on Climate Change (IPCC), the NRC, and other institutions, and to develop recommendations to improve the conduct and utility of future assessments. On the second day, five breakout sessions addressed applications of climate science to management of different sectors: water, ecosystems, coastal, air quality, and energy systems. The objectives of these five sessions were to:

- Discuss how well research is meeting the needs of decisionmakers
- Describe development and application of resources to support adaptive management and climate policy development
- Identify program needs and gaps.

Participants provided positive feedback on the opportunity to learn about CCSP's activities and exchange information with other scientists and decisionmakers. CCSP will use insights from the workshop to guide current and future CCSP programs, and intends to provide additional forums for communication about this aspect of the program in the future. A brief summary of key points raised during the workshop is available at <www.climatescience.gov/workshop2005>. This site also contains copies of workshop presentations and posters.

Decision-Support Resources Goal 1: Scientific Syntheses and Assessments

The *CCSP Strategic Plan* defines "assessments" as "processes that involve analyzing and evaluating the state of scientific knowledge (and the associated degree of scientific certainty) and, in interaction with users, developing information applicable to a particular set of issues or decisions." Assessments are an effective means for integrating and analyzing CCSP research results with other knowledge, and communicating useful insights in support of a variety of applications for decision support. Assessments also help identify knowledge gaps and thus provide valuable input to the process of focusing research.

A primary activity within CCSP is the development of 21 synthesis and assessment products to support informed decisionmaking on climate variability and change by a broad group of stakeholders, including policymakers, resource managers, media, and the general public. The development of these products stems from the Global Change Research Act (GCRA) of 1990 (P.L. 101-606, section 106), which directs the program to "produce information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change" and to undertake periodic science "assessments." The GCRA dictates that the

DESCRIPTION OF CCSP SYNTHESIS AND ASSESSMENT PRODUCTS

CCSP Goal 1: Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and changes.

Synthesis and Asssessment Product 1.1
Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences
Temperature change is a fundamental measure of climate change. This product, which is the first to be completed, addresses temperature changes from the surface through the lower stratosphere and our understanding of the causes of these changes. It assesses progress made since the reports by the National Research Council (2000) and the Intergovernmental Panel on Climate Change (2001) and highlights differences between the individual temperature records determined by components of the existing observational and modeling systems and documents the potential causes of these differences. See the Atmospheric Composition chapter for a summary of this report's conclusions.

Synthesis and Asssessment Product 1.2
Past Climate Variability and Change in the Arctic and at High Latitudes
The Arctic and the high latitudes have warmed more rapidly than almost any other region on Earth over at least the last millennium. This warming has been accompanied by a decrease in sea-ice cover and thickness and a decrease in ocean salinity. In addition, significant changes in the permafrost active layer are now being detected. Impacts on humans and ecosystems that are associated with these changes have recently been reported in the *Arctic Climate Impact Assessment*, which was partially funded by CCSP-participating agencies. The present synthesis and assessment product on the Arctic and high latitudes will focus on the state of knowledge concerning past changes in the physical climate of this region and the implications of this record of past changes for current and future change. This information is vital since high-latitude regions are projected to continue to experience the greatest warming in the future.

Synthesis and Asssessment Product 1.3
Re-Analysis of Historical Climate Data for Key Atmospheric Features: Implications for Attribution of Causes of Observed Change
A re-analysis is a detailed, retrospective study of the state of the atmosphere using a consistent numerical model of the dynamics of the system and based on observations for the time period of the study. This product will provide an assessment of the capability and limitations of state-of-the-art climate re-analysis to describe past and current climate conditions, and the consequent implications for scientifically interpreting the causes of climate variations and change. The product will be in the form of a report that summarizes the present status of national and international climate re-analysis efforts, and discusses key research findings on the strengths and limitations of current re-analysis products for describing and analyzing the causes of climate variations and trends that have occurred during the time period of the re-analysis records (roughly the past half-century). The report will describe how re-analysis products have been used in documenting, integrating, and advancing our knowledge of climate system behavior, as well as in ascertaining significant remaining uncertainties in descriptions and physical understanding of the climate system.

program's assessments should "analyze the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity." The scope of some of the synthesis and assessment products was recently revised to make them as responsive as possible to the GCRA.

DESCRIPTION OF CCSP SYNTHESIS AND ASSESSMENT PRODUCTS (CONT.)

CCSP Goal 2: Improve quantification of the forces bringing about changes in the Earth's climate and related systems.

SYNTHESIS AND ASSSESSMENT PRODUCT 2.1

A. Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations; and B. Global-Change Scenarios: Their Development and Use

This product consists of two components: (a) development of new scenarios of greenhouse gas emissions and atmospheric concentrations, and (b) a review of integrated scenario development and application. These two components are intended to contribute to and enhance the iterative international process of producing and refining climate-related scenarios and scenario tools. The first component will use several integrated assessment models as the foundation for a small group of new global emissions scenarios leading to long-term stabilization of greenhouse gas concentrations. The second component will review and evaluate how the science and stakeholder communities define, develop, implement, and communicate scenarios in the global climate change context, and how this process might be enhanced or improved. This will include a review of past scenario development and application efforts.

SYNTHESIS AND ASSSESSMENT PRODUCT 2.2

North American Carbon Budget and Implications for the Global Carbon Cycle

This product will provide a synthesis and integration of the current knowledge of the North American carbon budget (including land, atmosphere, inland waters, and adjacent oceans) and its context within the global carbon cycle. In a format useful to decisionmakers, it will summarize our knowledge of carbon cycle properties and changes relevant to the contributions of, and impacts upon, the United States and the rest of the world; and provide scientific information for U.S. decision support focused on key issues for carbon management and policy. It will address carbon emissions; natural reservoirs and sequestration; rates of transfer; the consequences of changes in carbon cycling; effects of purposeful carbon management; effects of agriculture, forestry, and natural resource management; and socioeconomic drivers and consequences. The report will include an analysis of North America's carbon budget that will document the state of knowledge and quantify uncertainties.

SYNTHESIS AND ASSSESSMENT PRODUCT 2.2

Aerosol Properties and their Impacts on Climate

Aerosols can cause a net cooling or warming within the climate system, depending upon their physical and chemical characteristics. In addition to these direct effects, aerosols can also have indirect effects on radiative forcing of the climate system by changing cloud properties. The first phase of development of this product is to produce major scientific reviews of the following three topics: dependence of radiative forcing by tropospheric aerosols on aerosol composition in the north Atlantic, Pacific, and Indian Ocean regions; measurement-based understanding of aerosol radiative forcing from remote-sensing observations; and model intercomparison to quantify uncertainties associated with indirect aerosol forcing. The second-phase product will draw upon the scientific information gathered by the development of the IPCC Fourth Assessment Report and the National Research Council review, "Radiative Forcing of Climate Change." These community-wide assessments of climate change (and the aerosol-climate topic inclusively) will be drawn upon when writing this synthesis and assessment product.

SYNTHESIS AND ASSSESSMENT PRODUCT 2.4

Trends in Emissions of Ozone-Depleting Substances, Ozone Layer Recovery, and Implications for Ultraviolet Radiation Exposure and Climate Change

Measurements of ozone-depleting gases in the atmosphere have shown that the concentrations of these gases are declining in response to the agreements reached under the Montreal Protocol. This report will provide an update on trends in stratospheric ozone, ozone-depleting gases, and ultraviolet radiation exposure; progress in improving model evaluations of the sensitivity of the ozone layer to changes in tropospheric composition and climate; and relevant implications for the United States. This information is key to ensuring that international agreements to phase out production of ozone-depleting substances are having the expected outcome: recovery of the protective ozone layer. The report will derive most of its information from recent international assessments of stratospheric ozone, ozone-depleting substances, and climate.

HCR Research on Assessment and Decision-Support Methods

CCSP supports research and tool development to advance the components of assessments that focus on human behavior and socioeconomic trends. Assessments need to incorporate projections of social and economic change (e.g., population and technological change) as well as the effects of environmental change on communities and sectors (e.g., transportation, health, agriculture, etc.). Decision support also requires methods and tools to undertake comparative work across communities, regions, and sectors. Highlights of some of this work are provided below.

Highlights of Recent Activities and Research

Development of Population Scenarios. Population scenarios have been developed with CCSP funding that bridge the gap between the socioeconomic scenarios (including input to greenhouse gas scenarios) developed by the IPCC and socioeconomic conditions at U.S. State levels. Population scenarios at the State level are needed to assess the consequences of global change for water quality, air quality, human health, and aquatic ecosystems. A new approach was used to develop State-level population projections that are consistent with IPCC assumptions and projections. This method preserves knowledge of the age distribution of the population over time.

Assessments of Transportation-Related Issues. An assessment of the greenhouse gas emissions benefits of heavy-duty natural gas and diesel vehicles in the United States

DESCRIPTION OF CCSP SYNTHESIS AND ASSESSMENT PRODUCTS (CONT.)

CCSP Goal 3: Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future.

SYNTHESIS AND ASSSESSMENT PRODUCT 3.1
Climate Models: An Assessment of Strengths and Limitations for User Applications
The topics addressed by this product are the strengths and limitations of climate models at different spatial and temporal scales. Its purpose is to provide information on the results from climate models, in ways that will allow the potential user of the information to evaluate how best it may be applied. The product will focus on natural and human-caused factors influencing climate variability and change during the period from 1870 to 2000. It will characterize sources of uncertainty in climate models and their implications for estimating future climate change. This product will be limited to models and their sensitivity, feedbacks, strengths, and limitations, rather than making specific future projections.

SYNTHESIS AND ASSSESSMENT PRODUCT 3.2
Climate Projections based on Emissions Scenarios for Long-Lived Radiatively Active Trace Gases and Future Climate Impacts of Short-Lived Radiatively Active Gases and Aerosols
This product will have two distinct components. The first will be to produce climate projections for research and assessment based on greenhouse gas emissions scenarios and atmospheric concentrations as reported in Synthesis and Assessment Product 2.1a. The second will be to produce climate projections for research and assessment based on emissions scenarios for methane and short-lived gaseous and particulate species developed by a number of global change research groups.

was undertaken to help improve the understanding of the potential for greenhouse gas emissions reduction though use of these vehicles. By evaluating existing CO_2 and other transportation-related greenhouse gas emissions data, this study identified future research and data needs to determine the emissions benefits of alternative-fueled heavy-duty vehicles. The study, *Assessment of Greenhouse Gas Emissions Benefits of Heavy Duty Natural Gas Vehicles in the U.S.*, can be found at <climate.dot.gov/papers.html>. In addition, an assessment of long-range transportation planning initiatives in northeastern states was conducted. This study examined the climate and energy benefit plans of northeastern States and assessed how transportation and long-range transportation planning fit into the development of State policy approaches to climate change. It addresses the status of State climate change programs, the inclusion of transportation in the programs, and how State departments of transportation could be more effective. This study, *Assessing State Long-Range Transportation Planning Initiatives in the Northeast for Climate and Energy Efficiency Benefits*, can be found at <climate.volpe.dot.gov/docs/final-bbg.pdf>.

Tools to Support Different-Place Collaboration of Climate Change Researchers.[10,13] Collaboratories are virtual places where teams of geographically distributed scientists engage in collaborative research. The NSF-, NOAA-, and USGS-supported Human-Environment Regional Observatory (HERO) project has been developing a collaboratory tool to support work by scientists studying the local- and regional-scale impacts of climate variation and change. The HERO toolkit includes

DESCRIPTION OF CCSP SYNTHESIS AND ASSESSMENT PRODUCTS (CONT.)

CCSP Goal 3 (continued)

Synthesis and Asssessment Product 3.3
Weather and Climate Extremes in a Changing Climate
The impact of climate extremes can be severe and wide-ranging. There is evidence that the economic impact of weather and climate extremes in the United States has increased over the past several decades, but the evidence for increases in extreme weather and climate events varies, depending on the event of interest. These events may be related to temperature parameters (severe freezes, heat waves), precipitation (wet spells, heavy precipitation events, droughts, ice and hail, snow cover and depth), or tropical and extra-tropical storm frequency. Identifying recent changes and trends in such parameters will be a focus of the report, as will be identifying what can be said about future changes. Since extreme weather and climate events on a global scale are regularly addressed in international assessments, this synthesis and assessment product will focus on weather and climate extremes primarily across Canada, Mexico, and the United States.

Synthesis and Asssessment Product 3.4
Abrupt Climate Change
The paleoclimate record reveals that Earth's climate can change rapidly and strongly between different stable states. Various scenarios portray future abrupt climate change large enough to pose a significant challenge to society. The goal of this product is to review and synthesize our current understanding of abrupt climate change and to identify gaps in our knowledge. The report will integrate information from the paleoclimate record, the instrumental record, and numerical model-based studies at various spatial scales. Key identified risks, such as changes in ocean thermohaline circulation and alteration of terrestrial hydrologic conditions (e.g., the location or amount of precipitation), will receive special attention because the potential impacts on society are large.

web and other Internet-based methods and tools to enable same-time (synchronous) and different-time (asynchronous) different-place collaboration. The toolkit supports same-time distributed meetings, including video links and shared visual display of geospatial information; different-time perspective-comparison and consensus-building activities; and long-term information sharing and knowledge development. Examples include an e-Delphi tool that supports the sharing and comparing of expert opinions, and a web portal that provides a personal workspace, mechanisms for forming groups and accessing group resources, and methods for encoding information with geographic referencing.

Highlights of Plans for FY 2007

The program's highest-priority activities in FY 2007 under its decision-support goal are the synthesis and assessment products. Illustrative highlights of other plans for FY 2007 are given below.

Knowledge Systems for Sustainable Development. In FY 2007, the final results of a multi-institutional study on Knowledge Systems for Sustainable Development will be communicated to a broad audience through a special, invited

DESCRIPTION OF CCSP SYNTHESIS AND ASSESSMENT PRODUCTS (CONT.)

CCSP Goal 4: Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes.

SYNTHESIS AND ASSSESSMENT PRODUCT 4.1

Coastal Elevations and Sensitivity to Sea-Level Rise

This product will examine the vulnerability of coastal areas in the U.S. mid-Atlantic states to sea-level change. Specific questions to be addressed include identifying which areas are low enough to be inundated by tides, how floodplains would change due to a changing climate, which areas might be subject to erosion, and locations where wetlands will be able to migrate inland versus locations where shores will be protected. The product will examine the implications of sea-level rise, including impacts on population and economic activity in vulnerable areas, costs of shore protection, ecological effects, flood damages, public access to modified shore areas, cases where sea-level rise justifies policy changes, options being considered by conservancies and governments, and lessons from the unfolding consequences of the 2005 hurricanes in the Gulf Coast region.

SYNTHESIS AND ASSSESSMENT PRODUCT 4.2

State-of-Knowledge of Thresholds of Change that Could Lead to Discontinuities in Some Ecosystems and Climate-Sensitive Resources

There is a body of ecosystems research that focuses on enhancing understanding of climate change impacts on ecosystems (and *vice versa*) and developing the capability to predict potential impacts of future climate change. Increasing emphasis is being placed on climate-related thresholds that could result in discontinuities or sudden changes in ecosystems and climate-sensitive resources. Discontinuities in responses of ecosystems and resources are difficult to predict, and may significantly affect human societies that depend on ecosystem goods and services. Improved understanding of such sudden changes is essential to managing ecosystems and resources in the face of climate change. This report will synthesize the present state of scientific understanding regarding thresholds of change that trigger sudden changes in ecosystems and climate-sensitive resources. The report will develop a conceptual framework for characterizing sudden changes, and synthesize peer-reviewed studies that provide the best available evidence for defining circumstances that trigger discontinuities in response to climate change.

DESCRIPTION OF CCSP SYNTHESIS AND ASSESSMENT PRODUCTS (CONT.)

CCSP Goal 4 (continued)

SYNTHESIS AND ASSSESSMENT PRODUCT 4.3
The Effects of Climate Change on Agriculture, Biodiversity, Land, and Water Resources
This report will address the effects of climate change on agriculture, forestry, land and water resources, and biodiversity. Temperature, precipitation, and related climate variables are fundamental regulators of biological processes. For this reason human-induced climate change has the potential to affect the condition, composition, structure, and function of ecosystems. Such changes may also alter the linkages and feedbacks between ecosystems and the climate system. Additionally, ecosystems produce a wide array of goods and services valued by humans. Climate-related changes in ecosystems and other key resources could have impacts on human communities and economic conditions.

SYNTHESIS AND ASSSESSMENT PRODUCT 4.4
Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources
Climate is a dominant factor influencing the distribution, abundance, structure, and function of, and services provided by, ecosystems. Many ecosystems are thus vulnerable to future changes in climate. The goal of adaptation is to reduce these risks of adverse ecological outcomes through management activities that increase the resilience of these systems to climate change. Resilience is defined here as the magnitude of disturbance that can be absorbed by a system before it shifts from one stable state (or stability domain) to another and the speed of return of a system to equilibrium after a disturbance has occurred. This report will provide a review and synthesis of information on adaptation options for selected climate-sensitive ecosystems in order to aid in designing management strategies that facilitate adaptation, provide examples of how to implement strategies in specific places, and identify issues and challenges associated with implementation of adaptation options.

SYNTHESIS AND ASSSESSMENT PRODUCT 4.5
Effects of Climate Change on Energy Production and Use in the United States
This product will summarize the current knowledge base concerning the possible effects of global change on energy production and use in the United States. It will survey and assess the available literature, paying attention to research findings on the implications of climate variability for energy production and use; identify and consider relevant studies carried out in connection with CCSP, CCTP, and other programs of CCSP agencies (e.g., DOE's Energy Information Administration); and consult stakeholders (e.g., the electric utility and energy industries, environmental NGOs, and academia) to determine what analyses have been conducted and what reports have been issued. Besides addressing questions of possible direct effects of climate change on energy consumption and production in the United States, the product will also consider how climate change might affect various factors that indirectly shape energy production and consumption, such as energy technology choices, energy institutional structures, regional economic growth, energy prices, energy security, and environmental emissions.

SYNTHESIS AND ASSSESSMENT PRODUCT 4.6
Analyses of the Effects of Global Change on Human Health and Welfare and Human Systems
The goal of this product is to examine linkages across physical, biological, and human systems in three separate assessments of the impacts of environmental change (climate variability and climate and land-use change) on human health and well-being. The assessment of human health will focus on the impacts of extreme heat and cold and extreme weather events, health effects of air pollution, water- and food-borne diseases, and vector- and rodent-borne diseases. The assessment of human welfare will consider the non-market welfare impacts on quality of life and on other valuations of aesthetics and human amenities. The assessment of human systems will examine the impacts of climate and land-use change on human settlements, including, for instance, the vulnerability of urban infrastructure to flooding; the potential impacts on water supplies resulting from warming, droughts, and flash floods; the dangers posed to human settlements by wildfire; and the effect of heat waves on fluctuations in energy demand in urban population centers.

SYNTHESIS AND ASSSESSMENT PRODUCT 4.7
Impacts of Climate Variability and Change on Transportation Systems and Infrastructure: Gulf Coast Study
This product will address potential effects of climate variability and change on transportation infrastructure and systems in the central Gulf Coast of the United States. The purpose of this study is to increase the knowledge base regarding the risks and sensitivities of transportation infrastructure to climate variability and change, the significance of these risks, and the range of adaptation strategies that may be considered to ensure a robust and reliable transportation network. Implications for all transportation modes—surface, marine, and aviation—will be addressed. The three-phase study will focus on the Gulf Coast, and will assess the significant risks to transportation, develop methodology to be applied in other geographic locations, identify potential strategies for adaptation, and develop decision-support tools to assist decisionmakers in incorporating climate-related trend information into transportation system planning, design, engineering, and operational decisions.

issue of the Proceedings of the National Academies of Science (PNAS). The Knowledge Systems project seeks to understand and promote the design of effective systems to harness research-based knowledge for sustainability. The project considers "knowledge systems" to be networks of linked actors, organizations, and objects that perform a number of knowledge-related functions (e.g., research, innovation, development, demonstration, deployment, and adoption) involved in linking knowledge with action. This work is particularly relevant to CCSP, given its emphasis on decision support. Prior to the special PNAS issue, findings of the project are being extended and evaluated through a series of workshops run in collaboration with the Roundtable on Science and Technology for Sustainability (see <www7.nationalacademies.org/sustainabilityroundtable/Sustainability_Roundtable_Homepage.html>).

This activity will address Questions 9.2 and 9.3of the CCSP Strategic Plan, and will support Decision Support Objective 1.1.

DESCRIPTION OF CCSP SYNTHESIS AND ASSESSMENT PRODUCTS (CONT.)

CCSP Goal 5: Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.

SYNTHESIS AND ASSSESSMENT PRODUCT 5.1

Uses and Limitations of Observations, Data, Forecasts, and Other Projections in Decision Support for Selected Sectors and Regions

This product will focus on characterizing a subset of the observations from remote-sensing and *in situ* instrumentation that are of high value for decisionmaking. The product will characterize observational capabilities that are currently or could potentially be used in decision-support tools, catalog a subset of ongoing decision-support activities that use these capabilities, and evaluate a limited number of case studies. The detailed evaluation of decision-support activities and demonstration projects will provide information to agencies and organizations responsible for developing, operating, and maintaining selected decision-support processes and tools. The evaluation will also provide information on the nature of interactions between users and producers of climate science information, approaches for accessing science information, and assimilation of scientific information in the decisionmaking process. The product will include an on-line catalog of decision-support demonstration projects with interactive links, which will be updated as additional experiments are conducted and new approaches to incorporating and benchmarking application of observations and other global change research products evolve.

SYNTHESIS AND ASSSESSMENT PRODUCT 5.2

Best Practice Approaches for Characterizing, Communicating, and Incorporating Scientific Uncertainty in Climate Decisionmaking

This product will address the issue of uncertainty and its relationship to science, assessment, and decisionmaking. Specifically, the product is intended to help improve the quality and consistency of information about scientific uncertainty presented to decisionmakers and other users of CCSP reports by identifying "best practice" options recommended in the literature on this subject; improve communication between scientists and users of the products by providing a simple "users' guide" on interpreting information about uncertainty contained in the reports; and provide a brief overview of the literature on approaches for taking account of uncertainty in decisionmaking.

SYNTHESIS AND ASSSESSMENT PRODUCT 5.3

Decision-Support Experiments and Evaluations Using Seasonal-to-Interannual Forecasts and Observational Data

This product will concentrate on the water-resource management sector. It will describe and evaluate current forecasts, assess how forecasts are being used in decision settings, and evaluate decisionmakers' level of confidence in these forecasts. The participants in the development of this product (primarily consisting of government officials, researchers, and users) will evaluate forecasts as well as their delivery, to identify options for improving partnerships between the research and user communities. It will inform decisionmakers about the experiences of others who have experimented with the use of seasonal and interannual forecasts and other observational data; climatologists and social scientists about how to advance the delivery of decision-support resources that use the most recent forecast products, methodologies, and tools; and science managers as they plan for future investments in research related to forecasts and their role in decision support.

Decisionmaking under Uncertainty Program. The increased knowledge generated by recent scientific research on the causes and consequences of climate change and variability has led to a growing need to better understand how decisionmakers can use this knowledge to make wiser choices. Five interdisciplinary research teams are studying important aspects of climate-related decisions under uncertainty over a 5-year period (see <www.nsf.gov/news/news_summ.jsp?cntn_id=100447&org=SBE>). Research centers are located at Arizona State, Carnegie-Mellon, and Columbia universities. Other interdisciplinary teams are conducting research at the University of Colorado at Boulder and Rand Corporation in California. Overviews of the activities of three of these centers follow.

- The Rand Center is conducting fundamental research on two key questions important to the design and use of decision tools for supporting climate change decisionmaking: What are the best ways to represent uncertainty for decisionmakers? What tools and methods work best in practice in providing these representations to decisionmakers? The project (see <www.rand.org/ise/projects/improvingdecisions/about.html>) strengthens the scientific foundations of robust decisionmaking, a promising new approach to computer-assisted support for decisions under conditions of "deep uncertainty" (e.g., when the likelihoods of different futures or the exact connection between policy actions and their effects is poorly understood). This research draws on interactions with decisionmakers in two policy areas: long-term planning for the management of water supplies by the California Department of Water Resources, and the design of scientific observation systems that could provide actionable warning of abrupt climate change.
- The Climate Decision Making Center at Carnegie-Mellon University (<cdmc.epp.cmu.edu>) is conducting research on limits in the understanding of climate change and its impacts. They are developing and demonstrating methods to characterize these irreducible uncertainties, focusing on uncertainties about climate and technologies for mitigation. They will also create, illustrate, and evaluate decision strategies and tools for policymakers that incorporate such uncertainties. The center's research focuses on the real-world problems of the following stakeholder groups:
  - Insurance managers who face financial risks from climate change and low-carbon technologies
  - Forest, fisheries, and ecosystem managers in the Pacific Northwest and Canada
  - Arctic-region decisionmakers trying to balance cultural lifestyles with economic development
  - Electric utility managers facing large capital-investment decisions in the face of climate risks.

In addition, the center will advance the current understanding of new low- or zero-carbon energy technologies that may be required by climate policy.

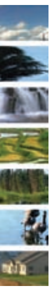
- The Center for Science Policy Assessment and Research on Climate (SPARC) at the University of Colorado (<sciencepolicy.colorado.edu/sparc>) examines the effectiveness of the relationship between science policy decisions and climate policy decisions. "Science policy decisions" are defined as those concerned with governing the climate science research enterprise. The Center distinguishes such decisions from "climate policy decisions," which are those made in anticipation of or in response to climate change. The relationship between science policy decisions and climate policy decisions has not been systematically examined. The SPARC research agenda will focus on two themes: reconciling supply and demand for climate research, which involves examining how research agendas are developed and how user demand for research is assessed; and sensitivity analysis, which involves examining how specific research issues are prioritized given the multiple causes of global environmental change. There are currently four SPARC research projects:
  - Climate Science Policy in the Regional Integrated Science and Assessment Program
  - Reconciling Supply and Demand – Carbon Cycle Science Activities
  - Ecosystem Function Sensitivity Analysis Activities
  - Extreme Events and Climate Change Sensitivity Analysis Activities.

This activity will address Question 9.1 of the CCSP Strategic Plan, support Decision Support Objectives 3.1 and 3.2, and applies to Synthesis and Assessment Product 5.2.

The National Research Council's Committee on the Human Dimensions of Global Change. As described above, this committee provides broad scientific expertise to CCSP. Additional soon-to-be completed studies relevant to CCSP include:

- *Public Participation in Environmental Assessment and Decision Making*. This major study was begun in 2001 to evaluate and summarize the state of knowledge about how to combine broadly based deliberation with scientific analysis to inform environmental decisions. A report is expected in mid-2007.
- *Confidentiality Issues Arising from Linking Remotely Sensed and Self-Identifying Data*: This study seeks ways to reconcile the conflicting needs for confidentiality and open access to data that are creating barriers to scientific efforts to gain knowledge by linking remotely sensed and self-identifying data. A report is expected in 2007.

This activity will address Question 9.1 of the CCSP Strategic Plan, and support Decision Support Objectives 2.2 and 3.1.



Decision-Support Resources Goal 2: Adaptive Management / Planning Decisions

A number of efforts are underway to support adaptive management and planning decisions (operational decisions for managing resources, societal response mechanisms, and long-term infrastructure planning). These activities include analyses for many sectors, including agriculture, forestry, water supply, and fisheries. Some of the main climate challenges being addressed for these sectors are drought and variations in the frequency of temperature extremes, severe precipitation, and runoff. Progress is being made to engage stakeholders at local and regional levels in an effort to bring information about the impacts of climate variability and change to bear on their management and planning decisions. Stakeholders include Governors' offices, State and Federal water management agencies, agricultural extension specialists, farmers, fisheries councils, wildland fire managers, and many others. Bringing climate science to these decisionmakers, analyzing the impacts of climate on their decisions, and collaborating with them to produce new knowledge and tools are all key parts of this component of CCSP. The following are some examples of progress in this area.

Highlights of Recent Activities and Research

Global Data Sources for Estimating Crop Production.[8] A report was published in 2005 documenting the initial steps toward improving estimates of crop production using next-generation space-borne Earth observation sensors. The Production Estimates and Crop Assessment Division (PECAD) of the USDA Foreign Agricultural Service uses NASA Earth science data products to improve the decisionmaking process through their analysis of monthly global crop production estimates of select agricultural commodities. The results of PECAD's global analyses of select commodities are communicated to the World Agricultural Board.

Sistema Regional de Monitoreo y Visualización (SERVIR) – The Mesoamerican Visualization and Monitoring System. On 1 February 2005, SERVIR, a regional monitoring and visualization system, was inaugurated for environmental and disaster decision support within Mesoamerica. It intensively utilizes satellite imagery, models, and other geoscience information that can be interactively used by scientists, educators, policymakers, students, and the general public to monitor and forecast ecological changes and respond to disasters such as forest fires, drought, and volcanic eruptions (see Figure 41). The tool includes space-based observations and predictive capabilities along with other geospatial data sets, interactive on-line maps, thematic decision-support tools, and three-dimensional interactive visualizations. The computational architecture of SERVIR also hosts data from other regional initiatives such as the Inter-American Biodiversity Information Network, and the United Nations Environmental Programme's Global Resource Information Database for Latin America and the Caribbean. The system is headquartered at the Water Center for the Humid Tropics of Latin America and the Caribbean in the City of Knowledge, Panama. A fully functional rapid prototyping center and test bed for the SERVIR facility is located at NASA's Marshall Space Flight Center in Huntsville, Alabama. The SERVIR functional capabilities are accessible online at <servir.nsstc.nasa.gov>.

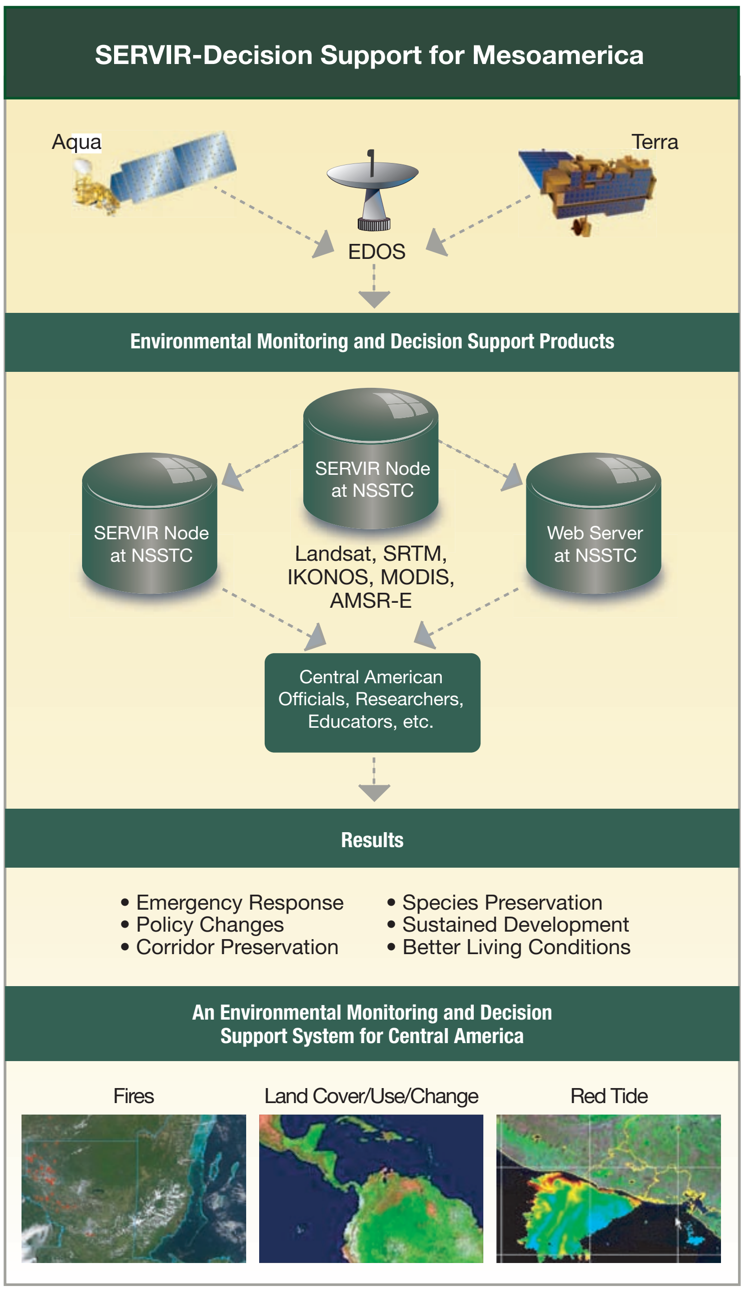


Figure 41: SERVIR – Decision Support for Mesoamerica. This schematic illustrates the components of SERVIR environmental and disaster support for Mesoamerica. *Credit: NASA/Science Mission Directorate.*

New York Climate and Health Project.[9] A team of climate and health scientists funded by NOAA, EPA, and NASA has been conducting interdisciplinary research on climate variability, climate change, land use, air quality, and human health in the New York Metropolitan Region. They have developed an integrated modeling system for assessing potential public health impacts related to heat stress and ground-level ozone. In particular, they linked a global climate model to regional climate models and a regional atmospheric chemistry model to produce downscaled heat and ozone estimates for the 1990s and the 2020s, 2050s, and 2080s under fast-growth and slower growth socioeconomic and climate scenarios and downscaled land-use scenarios (see Figure 42). A health risk assessment of mortality impacts was conducted at the county level with

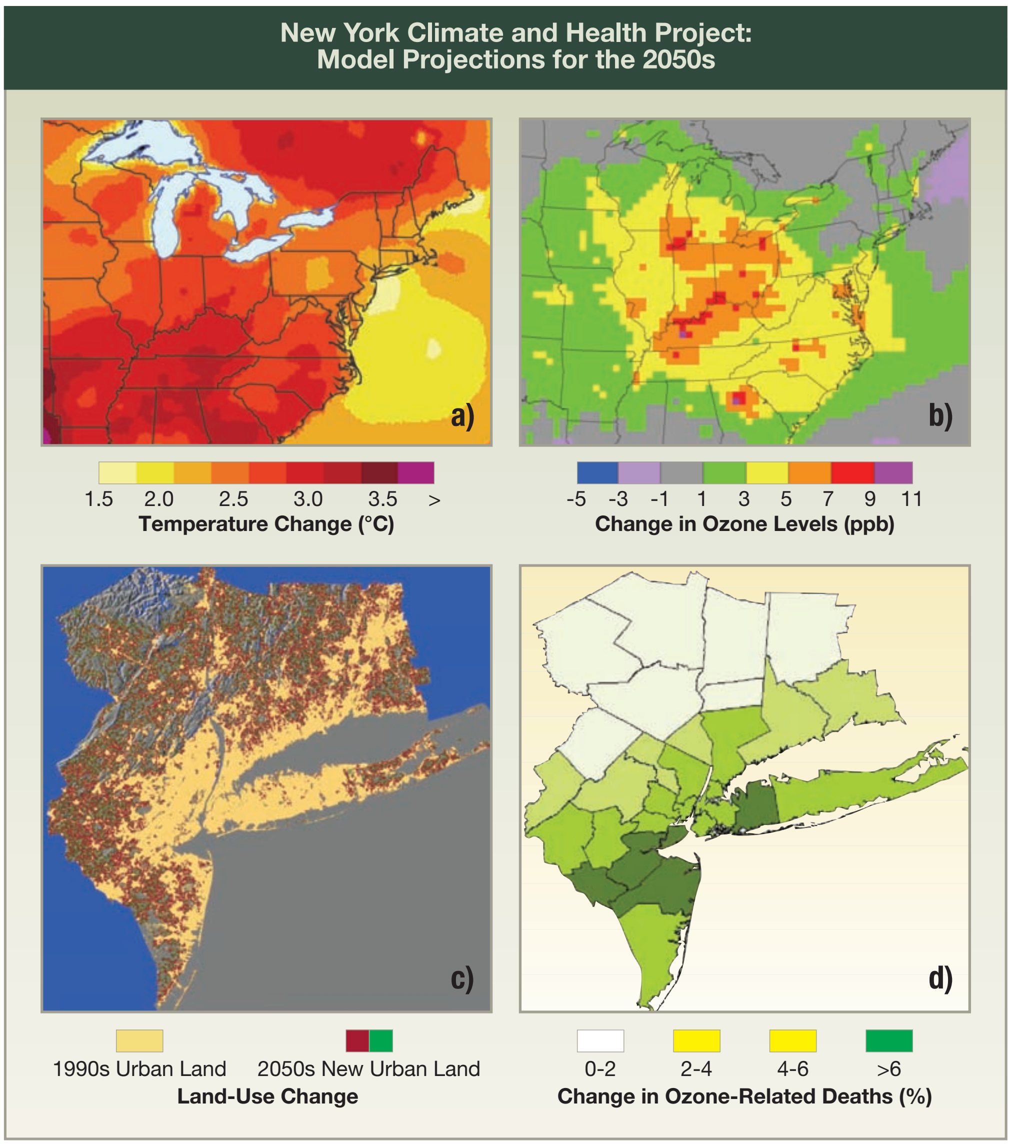
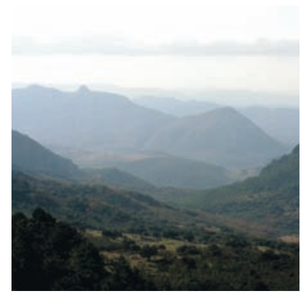


Figure 42: New York Climate and Health Project: Model Projections for the 2050s. These model projections employ the 2050 IPCC A2 emissions scenario: (a) temperature changes simulated with the Mesoscale Modeling System Generation 5 (MM5) regional model; (b) ozone changes simulated with the Community Multiscale Air Quality (CMAQ) modeling system; (c) land-use changes simulated with the Slope, Land-Use Elevation, Urban, Transportation, and Hillshading (SLEUTH) model; and (d) change in ozone-related deaths. *Credit: C. Rosenzweig, NASA/Goddard Institute for Space Studies (panel d reproduced with permission from* ***Environmental Health Perspectives****).*

these multi-model simulations of future environmental conditions. As part of this effort, more recent research has focused on providing improved understanding of climate and health vulnerability for stakeholders in support of decisionmaking in the New York region. This in-depth climate-health research is providing improved tools for decisionmakers in the region regarding public health risks due to potential heat and air quality changes.

Using Climate Change Information in Natural Resource Management: Considerations of Natural Resource Managers.[7] This research explored how resource managers and agencies are developing management activities to potentially address resource management under a changing climate. In listening to over 70 natural resource managers and professionals in the western United States, it was found that an understanding of climate variability and change was often an important consideration in the development of their management activities. Natural resource managers from Federal agencies, State agencies, and nongovernmental organizations are bringing the consideration of climate into the management arena through current institutional processes such as assessment, monitoring, focused research, education, planning, field-based activities, and mitigation. Natural resource managers tended to give greater consideration to climate change when scientifically accepted quantitative relationships between climate and a specific natural resource (e.g., water) were available and also when applications were available that could easily be used within the manager's current planning or management framework. Managers benefiting from partnerships with climate-focused organizations, extension staff, and/or scientists within their geographic areas were able to incorporate consideration of climate variability and change into the management planning processes.



Translating Climate Science for Natural Resource Management.[11] New information from climate sciences, including paleoecology, brings a new paradigm about natural vegetation dynamics and informs our ability to develop mitigation and adaptation strategies in light of future climate variability and potential change. Most of this has been inaccessible to natural resource managers. Approaches have been developed to translate scientific conclusions relevant to resource conservation and management so that resource professionals are be able to use this information in local and regional planning. One example of this is a rethinking of concepts of sustainability and restoration targets as well as approaches to future adaptation and restoration. Rather than restoring historic, "pre-human-disturbance" conditions, many species may persist better in the future by managing species populations so that they are realigned with current and anticipated future conditions, as well as through the provision of resource management options to cope with uncertain and highly variable futures.

AgClimate: A Prototype Decision-Support System for Using Climate Information to Reduce Risks in Agriculture

Research conducted by the NOAA- and USDA-supported Southeast Climate Consortium (SECC) has found that in some cases more than merely publishing climate forecasts is required if farmers and other decisionmakers are to use that information effectively. It is important for decisionmakers to have alternative response options. Crop simulation models, developed and tested during more than 30 years of research, allow the testing of both the effects of climate variability and potential crop management practices that can help reduce risks of crop or economic losses to extreme climate events. Using crop models and climate forecasts, the SECC released *AgClimate*, a prototype web-based decision-support system designed to help reduce the risks to agriculture that arise from climate variability (see <agClimate.org>)]. In addition to background information on climate and its role in agricultural systems, *AgClimate* includes a climate risk tool that can help users understand how the El Niño Southern Oscillation phase affects the temperatures and rainfall of their county; crop risk tools for peanut, tomato, and potato that can help farmers understand how climate affects these crops in their county and possible mitigation strategies for extreme climate events; a wildfire risk tool for foresters; and quarterly regional outlooks for climate and the application of climate forecasts to specific crops, which are developed and disseminated in cooperation with commodity extension specialists from the three states.

Refer to chapter references 1,2,4,5,6 for more detail.

New Research Products Developed to Better Support Western Water Management Decisionmaking.[14] CCSP-supported researchers through the Western Water Assessment (WWA) have developed a regularly updated web-based product, the "Intermountain West Climate Summary," available at <wwa.colorado.edu/products/forecasts_and_outlooks/intermountain_west_climate_summary>. This product has two main purposes: to provide climate information, in the form of graphics, current conditions, forecasts, verifications, and focus articles, to stakeholders in the water community in a format that is easy to read, understand, and access; and to improve the level of knowledge and understanding of forecasts and climate phenomena by potential users so that WWA researchers and operational providers can engage users in a more productive dialog to better understand their need for climate information and improve climate services.

In a separate effort, new tree-ring collections have been used to update reconstructions of Colorado River flows first generated in the 1970s, allowing for a longer calibration period for the reconstruction models. Multiple modeling approaches were used to test model sensitivity to differences in reconstruction methodology, and confirm the robustness of the final reconstructions. The reconstruction for the Lees Ferry gauge, which measures flow for the entire Upper Colorado River, a key source of water for seven states and parts of Mexico, indicates a higher long-term mean than seen in previous reconstructions. However, the long-term flow is considerably less than the baseline used to allocate Colorado River water resources in the 1922 Colorado River Compact. Additionally, more severe and persistent droughts than those found in the instrumental record have occurred in prior centuries. When the severe drought of 2000 to 2004 is compared to other 4-year droughts in the past, the reconstruction indicates that the severity of this drought was exceeded as recently as the mid-19th century. The recent drought rigorously tested the resiliency of Colorado

River Basin water-supply systems, and water managers are now more closely considering how this paleoclimatic information maybe be applied to drought planning and water resources management.

Famine Early Warning System Network. CCSP supports the innovative application of science to alleviate risks related to existing climate variability or the potential for climate change through the Famine Early Warning System Network (FEWS NET; see <www.fews.net>). FEWS NET provides decisionmakers with timely information to respond effectively to drought and food insecurity by analyzing remote-sensing data and ground-based meteorological, crop, and rangeland observations to identify early indications of potential famine. Through its programs, FEWS NET also supports capacity building in the developing world for climate forecasting and early warning network development. FEWS NET operates in 20 countries in Africa, three countries in Central America, and in Haiti and Afghanistan. In 2005, in addition to providing warnings of acute and emerging food crises, FEWS NET also provided analyses of long-term climate trends for decision support related to potential climate change impacts. For example, FEWS NET recently produced a special report detailing how warming in the Indian Ocean and changes in the monsoonal circulation pattern could reduce rainfall in Ethiopia. This information will allow development agencies and regional and local institutions to direct appropriate resources and support toward strengthening the adaptive capacity of affected food production systems.

Highlights of Plans for FY 2007

In FY 2007, CCSP-participating agencies will sponsor research to develop decision-support resources for adaptive management and planning for responding to climate variability and change, and develop collaborations to apply these research-based resources in operational settings. Selected examples follow.

Coping with Drought through Research and Regional Partnership. CCSP plans to launch a focused analysis of the social and economic impacts of drought. The work includes an analysis of the use of information about near-term climate variability and longer term climate trends to aid decisionmakers coping with drought. This effort is congruous with the Western Governors' Association's recommendation for a National Integrated Drought Information System (NIDIS); the strategic plan for NIDIS spells out the need for social and economic impacts research and the need for improved climate information. Research will focus on the development of methods, models, and mechanisms for evaluating the social and economic ramifications of drought and the policymaking and decisionmaking processes in the face of drought.

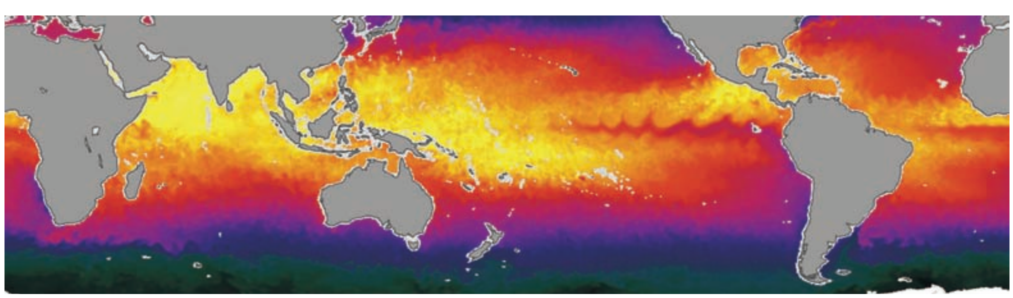
Potential climate information includes paleoclimatic and observed records of climate and its impacts, predictions based on seasonal-to-interannual climate variability, recent trends, and future projections of decadal variability and climate change. Social and economic impacts analyses will consider historical perspectives and near-term trends (e.g., projections of water conflicts, water demand, population changes, land-use shifts from rural to urban). Through this initiative, cutting-edge research on climate variability and change will be combined with in-depth analyses of the decisions made by the public and private sectors regarding drought. This effort will be conducted primarily through universities with strong partnerships among Federal and State agencies in drought-affected regions.

This activity will address Questions 9.2 and 9.4 of the CCSP Strategic Plan, and support Decision Support Objectives 2.1 and 2.2.

Adaptive Strategies for Transportation. The program is conducting various studies on adaptive management strategies for transportation to respond to climate change. One is a study of the effects of sea-level rise on national transportation infrastructure in order to identify specific infrastructure at risk. A series of studies, in cooperation with the Transportation Research Board of the National Academies, will focus on a reexamination of the role of design standards for transportation infrastructure in light of potential impacts from climate change, operational responses to potential climate change impacts, approaches to decisionmaking under uncertainty, and a case study of the transportation sector's response to and recovery from Hurricanes Katrina and Rita. These studies will be completed by early 2007.

This activity will address Question 9.2 of the CCSP Strategic Plan, support Decision Support Objectives 1.1, 2.1, and 3.1, and relate to Synthesis and Assessment Product 4.7.

Famine Early Warning System Network (FEWS NET). In 2007, FEWS NET (see <www.fews.net> and description above) plans to further analyze long-term climate trends in the Horn of Africa, building on their work in Ethiopia. Similar studies will be conducted in Somalia, Kenya, and Uganda. These studies will detail the relationship between temperature changes in the Indian Ocean and terrestrial temperature and precipitation changes across the Horn of Africa, and will analyze



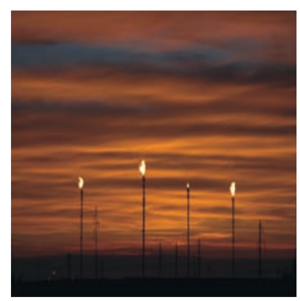
changes in the supply and demand for water based on changes in the precipitation regime of the region. In 2007, FEWS NET also plans to expand its network to Nigeria, conducting drought and food security analyses for that country and providing early warning of potential famine.

This activity will address Question 9.2 of the CCSP Strategic Plan, and support Decision Support Objective 2.2.

Transition of Research to Applications. The NOAA Climate Transition Program (NCTP) supports proposals for the transition of experimentally mature climate tools, methods, and processes from research to sustained operational delivery of useful climate information, products, and services to local, regional, national, and international decisionmakers and policymakers. NCTP seeks both to support implementation of these tools and to learn how better to accomplish transition technologies to support decisionmaking needs. NCTP supports well-defined partnerships between researchers, operations staff, decisionmakers, prototype developers, and extension, outreach, or education elements. In FY 2005, NCTP provided support for four projects (<www.climate.noaa.gov/index.jsp?pg=./cpo_pa/cpo_pa_index.jsp&pa=nctp&sub=3>).

This activity will address Questions 9.2 and 9.3 of the CCSP Strategic Plan, and support Decision Support Objective 2.2.

Decision-Support Resources Goal 3: Methods to Support Climate Policymaking



Climate is a primary or significant factor in a range of policy considerations including options for reducing greenhouse gas emissions, long-term ecosystem management, infrastructure planning in the public and private sectors, and science and technology research. CCSP, in collaboration with CCTP, is providing useful information related to these issues. For example, CCSP's carbon cycle research is exploring the permanence of various options for sequestering carbon. The program's ecosystem research is exploring the potential impacts of climate change on managed ecosystems and is assessing the potential efficacy and implications of options for managing ecosystems in the face of climate change. The program's water cycle research is examining ongoing changes in water availability in the western United States and options for coping with potential future changes in supply and demand. These and other policy-relevant research areas, many of which are discussed in earlier chapters, are part of CCSP's efforts to develop information useful for policymaking.

CCSP also supports the development of integrated modeling frameworks that are useful for exploring many dimensions of climate and global change. Integrated analysis of climate change is essential for bringing together research from many contributing disciplines and applying it to gain comparative insight into policy-related questions. Full integration of information including research on human activities, greenhouse gases and aerosol emissions, land-use and land-cover change, cycling of carbon and other nutrients, climatic responses, and impacts on people, the economy, and resources is necessary for analysis of many important questions about the potential economic and environmental implications of changing greenhouse gas concentrations and various technology portfolios. Development and use of techniques for scenario and comparative analysis are useful for exploring the implications of different hypothetical policies for curbing emissions growth or encouraging adaptation. Answers from integrated analysis can only reflect the existing state-of-knowledge in component studies, but it is important to develop frameworks and resources for integration, exercise them, and learn from analysis of the results. CCSP is encouraging innovation and development of approaches to integrated analysis.

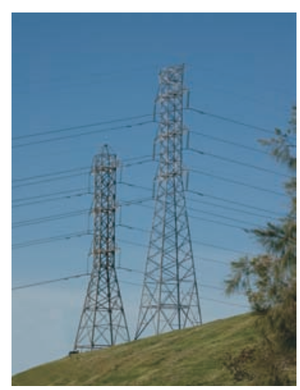
An integrated assessment of climate change analyzes the human (including economic), physical, and biological aspects of climate change, from the forces that give rise to greenhouse gas emissions or land-cover/land-use change (such as economic activity, demographic change, and technological advance), through emissions, to impacts (such as changes in unmanaged ecosystems, sea-level rise, and altered growing conditions for crops). The primary emphasis in an integrated assessment is to represent all three aspects in such a way that the costs and benefits of climate change can be evaluated. Integrated assessments are commonly based on scenarios simulated using a computer model. Integrated assessment models are used to evaluate, for example, specific climate change policy options, including those for reducing greenhouse gas emissions.

Highlights of Recent Activities and Research

Determinants of Residential Water Consumption.[3] Decision Center for a Desert City, a Decision Making Under Uncertainty Center supported by NSF, has been studying water consumption. Municipal water records at the census tract level were obtained from the City of Phoenix and related to information from other sources about lot size, the presence of pools, household size, and landscaping style. Least-squares regression was used to identify the determinants of single-family residential water use in Phoenix in 2000 and geographically weighted regression to determine whether the behavior of nearby areas affects local water demand. Results substantiate the significance of household characteristics (size), urban design features (lot size and pools), and landscaping practices (mesic vegetation) on residential water demand and point to a strong spatial bias in water consumption. Households tend to use water at a level comparable to their neighbors, irrespective of their demographic and urban design features. Thus, planning decisions may have different effects in different parts of the city. Model parameters will be used to estimate demand under different urban-growth and planning scenarios. The results of this study, in conjunction with analyses of climate variability and change, are being used to assess the relationships between climate and water consumption in an arid metropolitan region.

Comparing the Potential Effect of Cap-and-Trade Policies on Sectors with Existing Tax Regimes in the United States and the European Union.[12] One of CCSP's decision-support approaches is to conduct "If…, then…" analyses of climate change response options. Recent research has included an explicit representation of existing tax regimes in a quantitative analysis of potential strategies for reducing greenhouse gas emissions. The household transportation sector is among the more rapidly growing energy users, and fuel inputs are often taxed at much higher rates in transportation than in other areas of the economy. In addition, policies directed toward energy use and environmental control generally have given special treatment to the transportation sector (particularly the automobile). The European Union, for example, excludes the transportation sector from the 2005-2007 trial period of its emissions trading system. In the absence of pre-existing tax distortions, as is the case in the United States, exemption of transportation sectors would imply increased carbon tax rates for other sectors and higher costs for the economy as a whole. For the European Union, on the other hand, the exemption of the already highly taxed transport sector may actually decrease the estimated cost of meeting a carbon constraint, even when the capped sectors are required to cut further to make up for the sector exemptions.

Highlights of Plans for FY 2007



Comparison of Policy Assessments with Different Types of Economic Models. A comparison of the effectiveness of economic instruments, such as the costs of national cap-and-trade measures predicted by integrated assessment models, often reveals significant differences among models. One source of divergence is the way models represent expectations for future developments—that is, whether a model is forward-looking (current decisions are based on future as well as current prices) or recursive dynamic (each time period is analyzed independently). Forward-looking models sometimes show higher costs during initial control periods, apparently because solutions result in larger reductions in consumption early in anticipation of a future tightening of the constraint. Resolution of these differences in results is difficult because these varying models, developed by different groups, have substantial differences in structure, assumptions, and the way expectations are modeled. The Massachusetts Institute of Technology Joint Program on the Science and Policy of Global Change will complete development of a multi-sector, multi-region economic model (specifically, a computational general equilibrium model) that can be run in either forward-looking or recursive-dynamic mode. Carefully controlled simulations with this model will provide a basis for explaining the origin of the differences among model types and explain some of the existing variation in predicted costs.

This activity will address Question 9.1 of the CCSP Strategic Plan, support Decision Support Objectives 2.1 and 3.1, and relate to Synthesis and Assessment Product 2.1.

Emissions Analysis of Freight Transport Comparing Land- and Water-Side Short-Sea Routes: Development and Demonstration of a Decision Modeling Tool. The goal of this study is to develop a methodology and tools to compare greenhouse gas and other emissions from land- and water-side freight transport alternatives. Current efforts to investigate and promote the use of short-sea shipping alternatives (inland and coastal waterways used to move commercial freight from major domestic ports closer to final destinations) will benefit from additional information that compares emissions of greenhouse gases and other pollutants among freight modes. The tools and methodology that come out of this study will contribute to developing best practices for greenhouse gas mitigation in the multi-modal freight sector. Completion is expected in early 2007.

This activity will address Questions 9.1 and 9.3 of the CCSP Strategic Plan, support Decision Support Objectives 2.1, 2.2, and 3.2, and relate to Synthesis and Assessment Product 4.7.

Transportation-Focused Studies. Outside of Synthesis and Assessment Product 4.7, DOT is conducting the following two studies to support informed discussion of the relationships between transportation and climate change. In light of President Bush's goal for an 18% reduction in greenhouse gas intensity by 2012, a study will be completed in 2006 aimed at quantifying transportation's current contributions to overall U.S. greenhouse gas intensity. In addition, in FY 2007, a comparative analysis of emissions from aviation, automobile, marine, and diesel transport will be undertaken. This study will compare emissions data sets from aviation, heavy-duty diesel, automobile, and marine vehicles and analyze the similarities and differences across the transportation modes. The final report will determine how the analyzed data can be added to existing emissions inventories and used in quantifying contributions to local and regional air quality and climate change.

This activity will address Question 9.1 of the CCSP Strategic Plan, support Decision Support Objective 1.1, and relate to Synthesis and Assessment Products 2.1 and 4.7.

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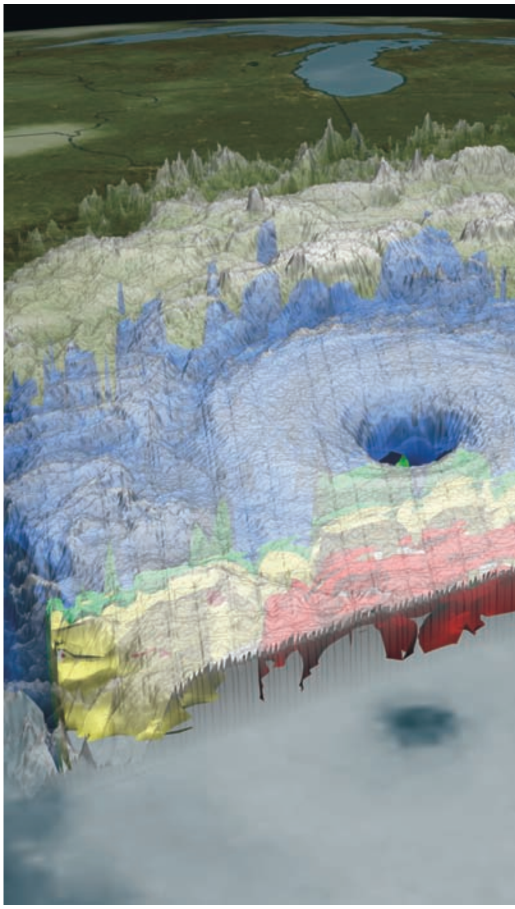
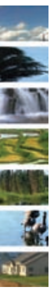




8 | Observing and Monitoring the Climate System

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.

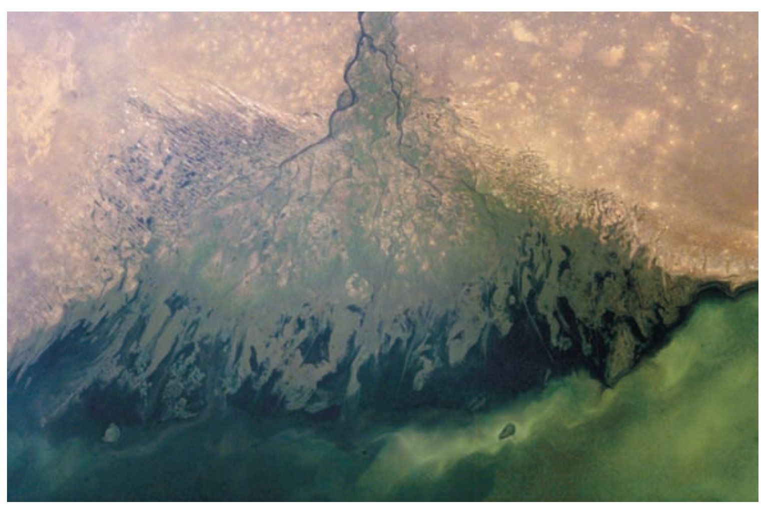
See Chapters 12 and 13 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of these goals.

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.

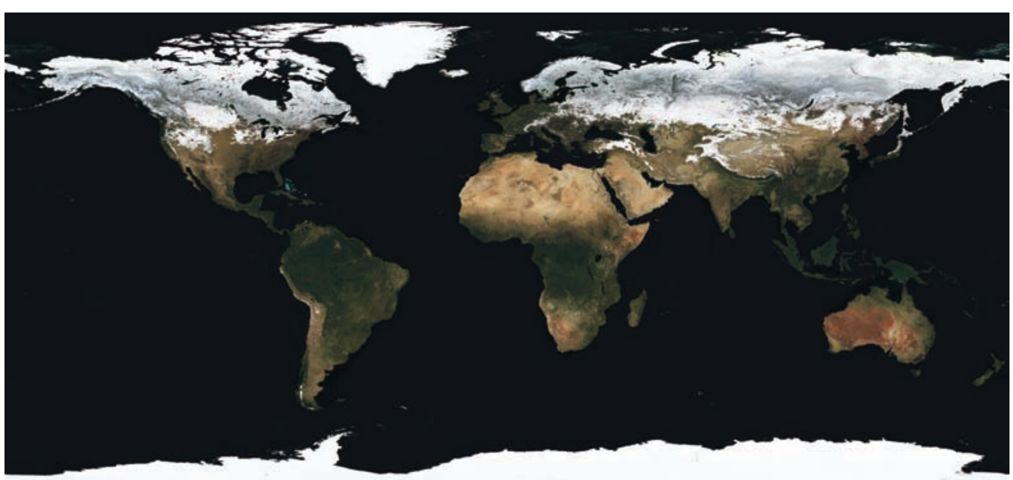
The United States is also playing an important role in the Global Earth Observation System of Systems (GEOSS), which is an international framework for coordinating and sustaining the aforementioned (and other) systems. Information from GEOSS is expected to revolutionize understanding of the Earth and 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>.

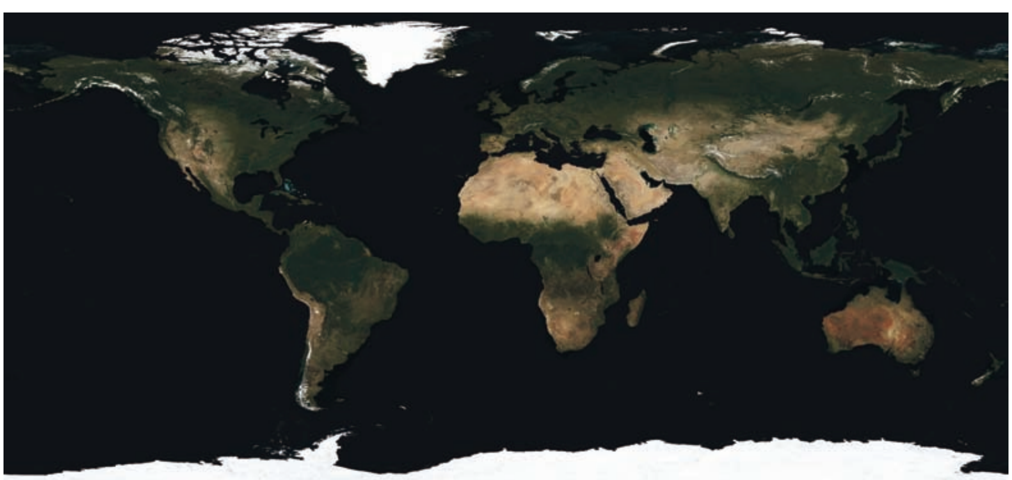
The Global Climate Observing System (GCOS) integrates global networks placed strategically across the atmospheric, oceanic, and terrestrial domains, permitting

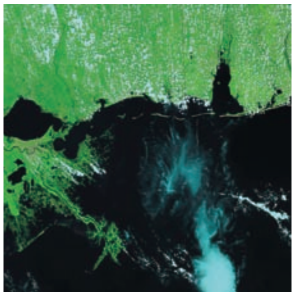


better understanding of climate variability and change. In recent years, GCOS has encouraged, coordinated, and facilitated a number of positive actions on international, regional, and bilateral levels that have led to success in improving climate observations worldwide. A number of workshops have been 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.

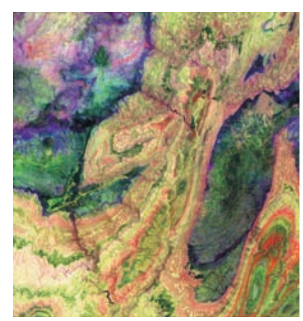
The top three priorities of CCSP relate to aerosols, the carbon budget, and polar climate/feedback. The Observations Working Group's contributions to those priorities include:

- 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)

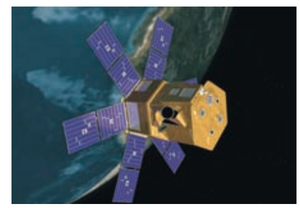
- Global mapping of cloud heights and aerosols with unprecedented sensitivity and detail
- Sensing of vegetation canopy heights and density
- Precision mapping of land elevations.

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).

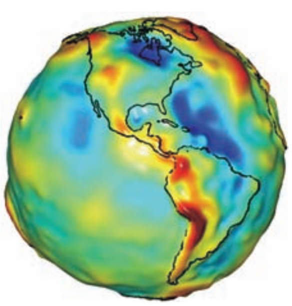
QuikSCAT.[2,6] The SeaWinds instrument aboard the Quick Scatterometer (QuikSCAT) satellite has measured the speed and direction of wind over the surface of the oceans since 1999. Although launched as an experimental instrument, it has been assimilated pre-operationally into atmospheric weather prediction 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.

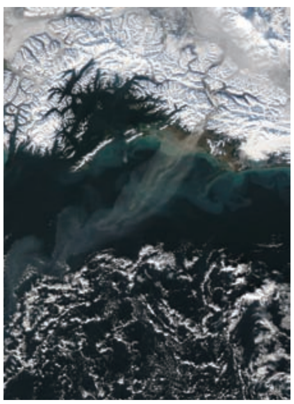
Earth Observing System Data and Information. NASA's Earth Observing System Data and Information System (EOSDIS) provides convenient mechanisms for locating and accessing products of interest either electronically or via orders for data on media. EOSDIS facilitates collaborative science by providing sets 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.

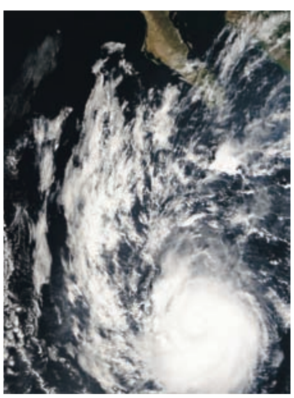
Lasting 24 months, IPY will include two summer field seasons in both hemispheres, permitting more extensive observations and helping to establish a durable network of polar observatories supported by numerous polar countries. IPY links to the Electronic Geophysical Year are intended to make IPY data 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

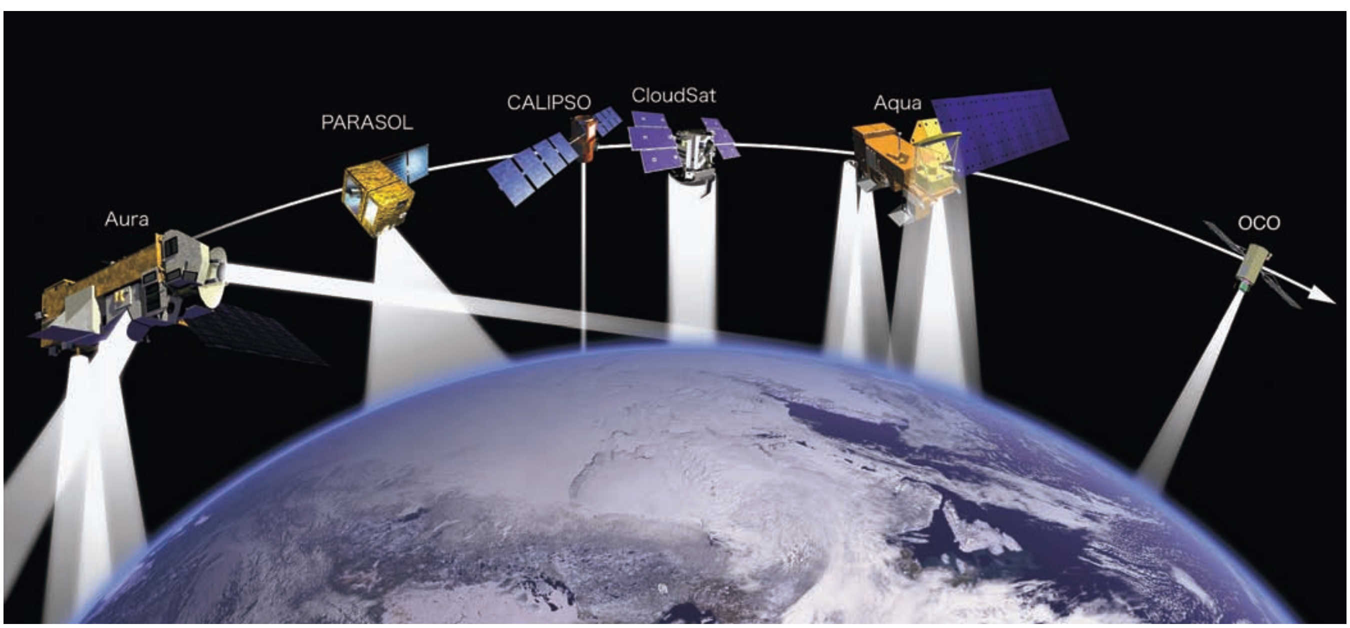
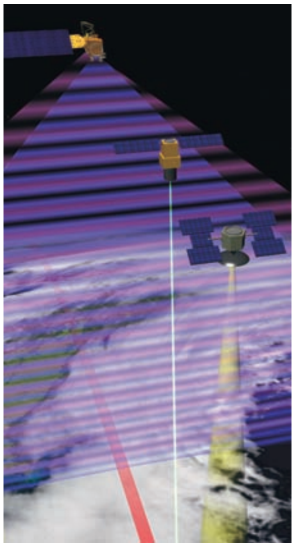
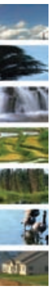


Figure 43: The "A-Train." This figure illustrates the constellation of satellites known as the "A-Train," which are making nearly contiguous observations of many facets of the Earth system. *Credit: NASA.*





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.

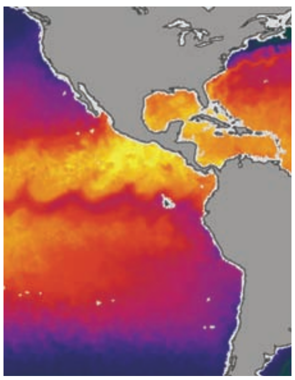
These activities will address Goals 12.1 and 12.5 of the CCSP Strategic Plan.

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>.

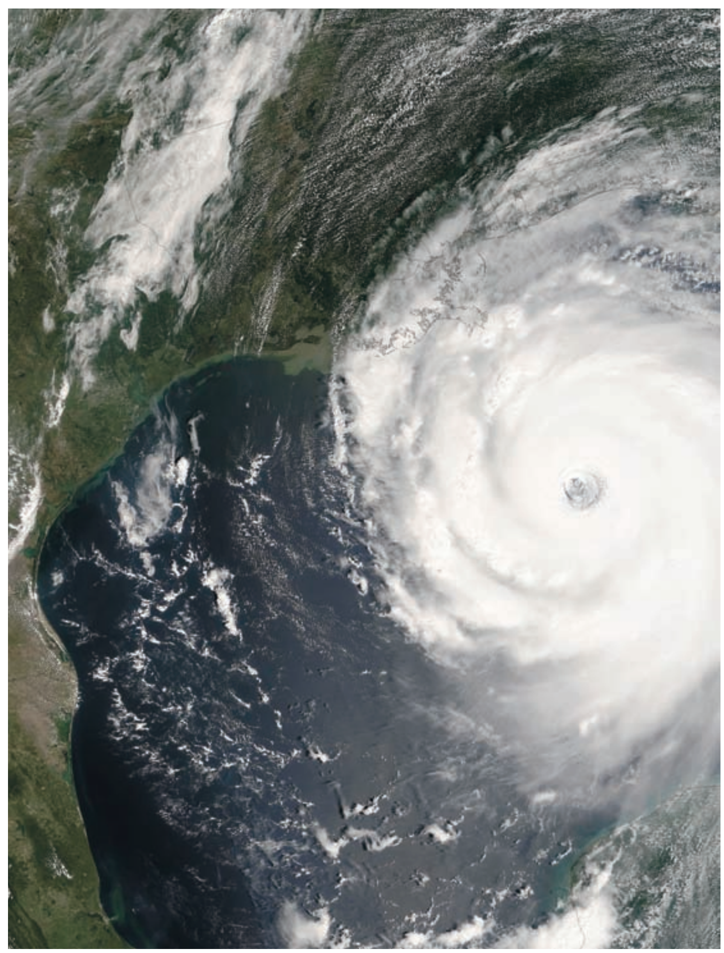
These activities will address Goals 12.1 and 12.5 of the CCSP Strategic Plan.

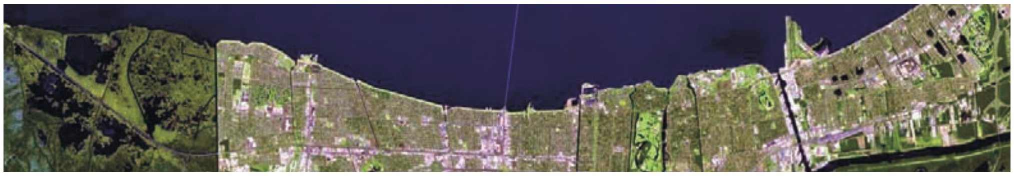
African Monsoon Multidisciplinary Analysis. African Monsoon Multidisciplinary Analysis (AMMA) is an international project to improve our knowledge and understanding of the West African Monsoon (WAM) and its variability, with an emphasis on daily-to-interannual time scales. AMMA is motivated by an interest 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.

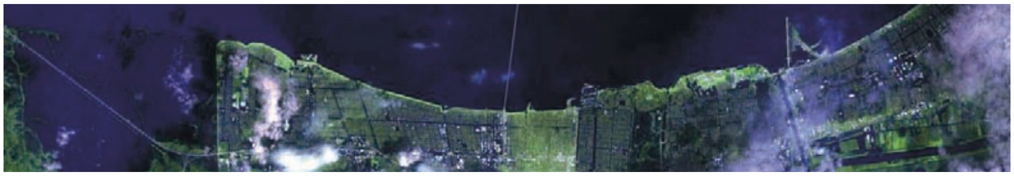




Data Fusion. As the length-of-record in the database of global observations increases, additional effort will be placed on assimilating Earth observations into GCMs, to produce an integrated view of the climate system and to better provide this view to users as part of decision-support and resource management 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.

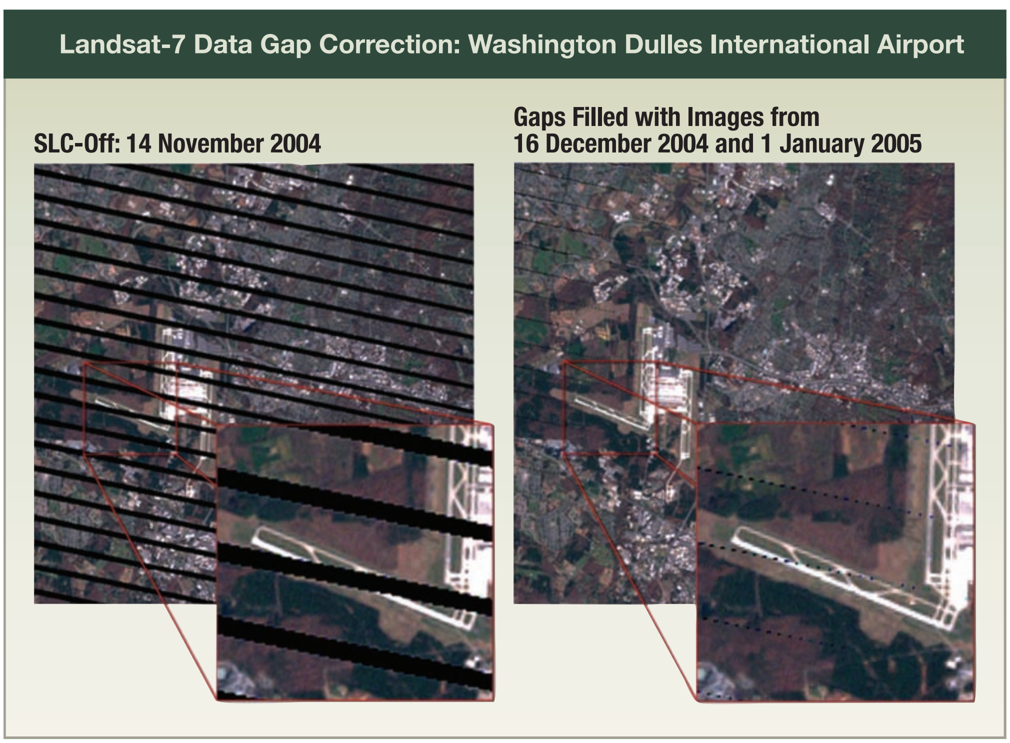


Figure 44: Landsat-7 Data Gap Correction: Washington Dulles International Airport. These products represent a portion of a false-color Landsat-7 scene over the Dulles airport area in Virginia, showing the gap-filled product developed to compensate for a mechanical problem on Landsat-7. *Credit: R. Beck,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

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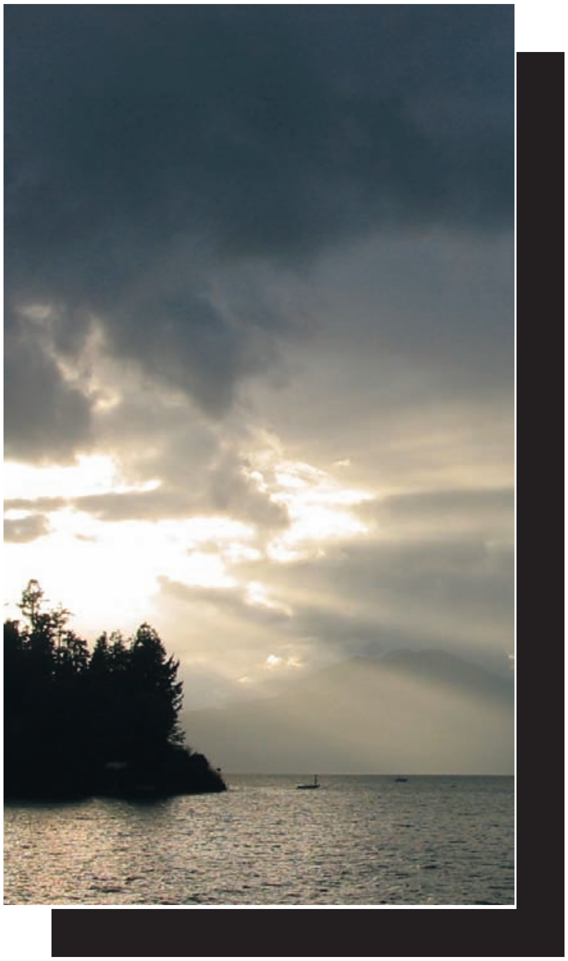


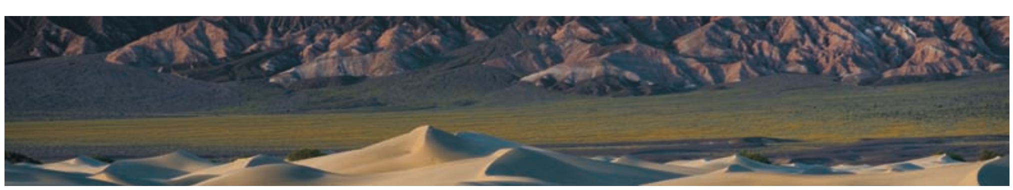
9 | Communications

The CCSP, in its vision for the program, identified communications as one of four core approaches for achieving its five overarching scientific goals. The CCSP is committed to communicating with interested partners in the United States and throughout the world, and learning from these partners on a continuing basis. As an essential part of its mission, the CCSP stresses openness and transparency in its findings and reports.

The Communications Interagency Working Group (CIWG), established during FY 2004, develops and executes an implementation plan each year that focuses on disseminating the results of CCSP activities credibly and effectively and making CCSP science findings and products easily available to a diverse set of audiences. Elements of the implementation plan for calendar year 2006 include:

- *Media Relations* – when requested by the CCSP Director, assisting in communicating on matters relating to climate science
- *Public Outreach* – developing materials and methods for public outreach on issues related to climate science and the activities and products of CCSP
- *Web Sites* – developing and advancing a strategy for improving, integrating, and promoting the content of web sites operated or supported by CCSP and its participating agencies, recognizing that the sites are essential communication and outreach tools.

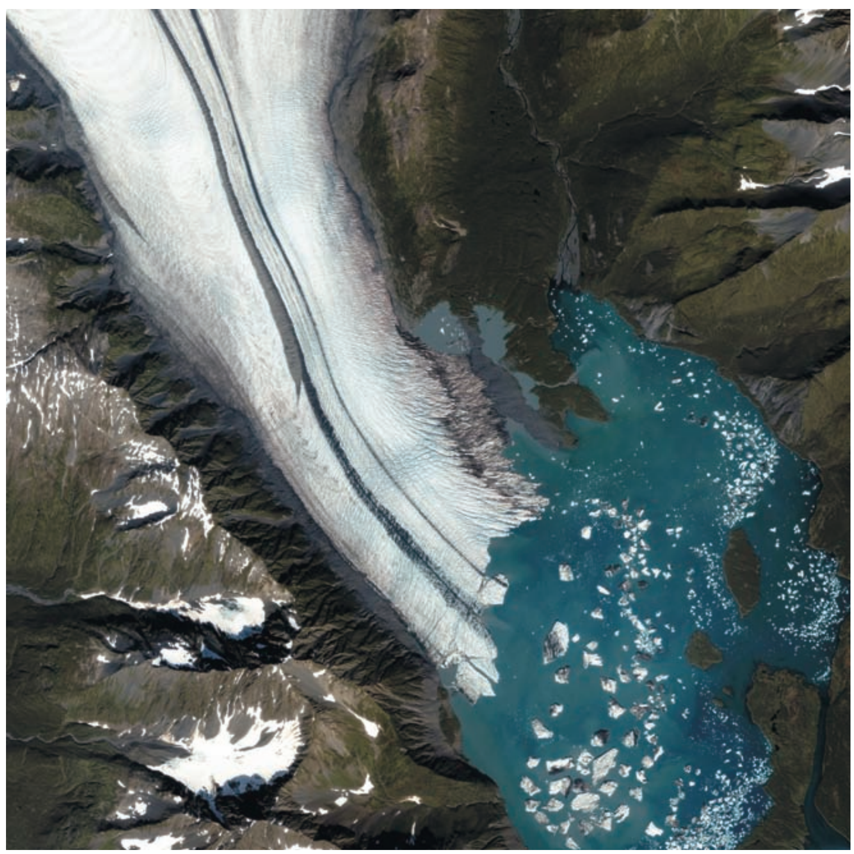
The Climate Change Science Program Office (CCSPO), funded and supervised by the agencies and departments participating in CCSP, supports the program's communications goals, along with members of the CIWG. CCSPO assists the CIWG, coordinates preparation of the annual *Our Changing Planet* report to Congress as well as other reports, and is responsible for managing the program's interagency web sites.

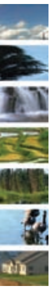


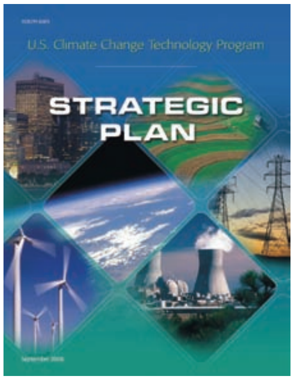
Highlights of Recent Interagency Communications Activity

Listed below are highlights of recent communications activities coordinated at the interagency level:

- Published and distributed *Our Changing Planet: The U.S. Climate Change Science Program for Fiscal Year 2006*.
- Published seven basic information sheets: Overview of the U.S. Climate Change Science Program, Overview of the CCSP Research Elements, Overview of the CCSP Strategic Plan, Overview of the CCSP Budget, CCSP Synthesis and Assessment Products, Methane as a Greenhouse Gas and an overview of the CCSP Annual Report to Congress *Our Changing Planet*.
- Added new material to CCSP's publicly accessible web sites, including the FY 2006 edition of *Our Changing Planet* and materials relating to CCSP's synthesis and assessment products. These include draft and final prospectuses that provide background information on each planned report and a detailed roadmap that will be followed in producing it. CCSP also posted the public review and final drafts for the first synthesis and assessment product (*Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*). These postings help ensure early and ongoing review of synthesis and assessment products by stakeholders.
- Facilitated stakeholder participation in the U.S. Government review of draft documents of the Intergovernmental Panel on Climate Change (IPCC).
- Sponsored the CCSP workshop, *Climate Science in Support of Decision Making*, for scientists and stakeholders in November 2005.
- Managed and improved CCSP web sites. Traffic to CCSP's three main sites increased to over 7,000 visits per day by December 2005, a 53% increase over December 2004. CCSPO also improved web services to facilitate interagency collaboration.







- Managed the Global Change Research Information Office (GCRIO). Mandated by the Global Change Research Act of 1990, the purpose of the office is to "disseminate to foreign governments, businesses, and institutions, as well as the citizens of foreign countries, scientific research information available in the United States which would be useful in preventing, mitigating, or adapting to the effects of global change." GCRIO includes a major web site, with two important features:
  - The GCRIO online catalog for requesting reports and CDs. Relative to FY 2004, the average number of orders received per month increased 94% in FY 2005, and the average number of products shipped per month increased 408% over FY 2004.
  - *Ask Dr. Global Change*, which provides answers to global change questions submitted by web site visitors.
- Managed the CCTP public web site, where the number of visits doubled between December 2004 and December 2005. CCSPO also provides additional support services to CCTP, including development and management of password-protected web sites and publications support.

Highlights of CCSP Interagency Communications Plans for FY 2007

Listed below are some of the communications activities coordinated at the interagency level that are planned for FY 2007:

- Ensure early and ongoing review of draft synthesis and assessment products by stakeholder communities and promote the release of final synthesis and assessment products, communicating information about their availability and key findings. CIWG will advise the synthesis and assessment product teams and lead agencies on communications-related issues including: dissemination to appropriate stakeholders, briefings, press releases, and summaries for a range of audiences across different information media.

- Prepare, publish, publicize, and disseminate the FY 2008 edition of *Our Changing Planet*.
- Facilitate stakeholder participation in the U.S. Government review of draft IPCC documents.
- Continue to improve and expand web sites by preparing and posting new web content, improving web site usability and accessibility, enhancing integration between agency and interagency web sites, and expanding web services to CCSP working groups.

10 | International Research and Cooperation

During FY 2007, CCSP will continue to cooperate and coordinate its research with its international partners, particularly through international programs and related activities of wide agency interest that are intended to advance understanding of climate and global change. Individual agencies also support international programs and activities that aid the agency in addressing its mission and, in many cases, also contribute to national objectives. To promote effective international coordination of these programs and activities, CCSP provides from distributed costs a U.S. share of multilateral support for such coordination.

Additional activities supported by CCSP, updated here, include capacity building, a wide variety of international assessment and decision-support activities, bilateral arrangements in climate change science and technology, and a wide range of additional climate-related cooperative and coordination activities.

CCSP participates in and provides input to four major international scientific and related organizations on behalf of the U.S. Government and scientific community. It does so in part through its working groups, including the Interagency Working Group on International Research and Cooperation. In addition, CCSP promotes and encourages the broadest possible participation of U.S. scientists and scientific institutions in international climate science.

These international global change research programs—the World Climate Research Programme (WCRP), the International Human Dimensions Programme (IHDP), the International Geosphere-Biosphere Programme (IGBP), and DIVERSITAS—are now coordinating and integrating their activities through the Earth System Science Partnership (ESSP). The SysTem for Analysis, Research, and Training (START) also receives strong U.S. support for its activities to promote outreach and capacity building that support the WCRP, IGBP, IHDP, and DIVERSITAS. The United States also actively encourages regional cooperation in climate change research, especially through its support of regional global change research networks such as the Inter-American Institute for Global Change Research (IAI), and the Asia-Pacific Network for Global Change Research. Most recently, with cooperation from ESSP, the United States provided support for a successful workshop to explore needs and opportunities for more formal cooperation in global change research in Africa.

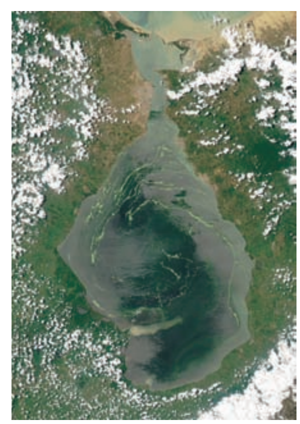
The United States continues to encourage international cooperation in the development of observing systems through its continued participation in the Global Earth Observation System of Systems (GEOSS).

The United States also continues to cooperate with its partners in a number of international scientific assessment and decision-support activities such as the Intergovernmental Panel on Climate Change (IPCC), the World Meteorological Organisation (WMO)/United Nations Environment Programme (UNEP) ozone assessments, and other applications-related programs such as the International Research Institute for Climate Prediction (IRI).

The United States, through CCSP agencies, supports advancement of several Presidential international initiatives including the suite of 15 climate change bilateral agreements coordinated by DOS.

Updates regarding these and other key international activities follow. For more detailed background information on these international activities, see Chapter 15 of the *Strategic Plan for the U.S. Climate Change Science Program*.

Cooperation in Support of International Research Programs



World Climate Research Program. WCRP focuses on fundamental understanding of the physical climate system, improvement of predictions, and understanding the extent of human influence on global change. In so doing, WCRP's activities are closely tied to the goals of CCSP, especially Goals 1, 2, and 3. WCRP has made significant progress this year in planning for implementation of its new cross-cutting multidisciplinary strategic framework for Coordinated Observation and Prediction of the Earth System (COPES). A WCRP team recently made a series of visits to a number of CCSP agencies to explain their planning and proposed implementation of COPES.

The WCRP Coordinated Enhanced Observing Period (CEOP) has developed a prototype observing system of systems for the global water cycle, involving 35 reference sites, national and international space agencies, and 11 operational numerical weather prediction centers. Composite CEOP products are being used to assess the quality of operational numerical weather forecasts and climate models. Researchers and scientists involved in operational climate forecasting systems are also making considerable use of data from the tropical observing system, first developed in the Pacific under the auspices of the WCRP Tropical Ocean Global Atmosphere project and now expanded into the Atlantic and planned for the Indian Ocean.

The WCRP Climate Variability and Predictability (CLIVAR) project has launched a study to determine the extent to which seasonal prediction across the globe is possible and useful with currently available models and data. It is coordinating ongoing activities in about 10 research and forecast centers around the world, evaluating and comparing the performance of the present systems, encouraging the exchange of model results, and organizing joint pilot numerical experiments.

WCRP's longer term strategy is to organize coordinated prediction and predictability experiments with ocean-land-atmosphere models that will ultimately lead to seamless weekly, seasonal, interannual, and decadal forecasts. This requires that the roles of the atmosphere, ocean, land, and cryosphere be properly simulated in comprehensive models of the climate system, which are also capable of assimilating weather and climate observations. This calls for a sustained research effort in validating and developing climate models and data assimilation techniques. An important test of success will be the validation of climate models through their ability to simulate past climate variability, including abrupt climate changes.

Major scientific progress in studies of the water cycle, precipitation regimes, and water resources was summarized at the fifth International Global Energy and Water Cycle Experiment (GEWEX) Conference, held in June 2005, in California. Continental-scale experiments are still underway to study the components of the water cycle over the major continents, including North and South America, Eastern Asia, and Australia, and a new experiment in Africa has been launched with the support of WCRP. The African Monsoon Multidisciplinary Analysis (AMMA) has begun a multi-year field campaign over West Africa and the tropical Atlantic, designed to improve understanding of the West African Monsoon and its influence on regional and global climate. It includes physical, atmospheric chemistry, and biological studies of interest for sustainable development in Africa, and includes components dealing directly with health, water resources, food security, and demography.

WCRP expects to focus in the coming year on areas of particular interest to the United States. These include research on improving seasonal-to-interannual prediction through CLIVAR; on the water cycle, precipitation regimes, and water resources; on monsoon processes and forecasting; on atmospheric chemistry, stratospheric processes, and climate,

especially through a new joint WCRP-IGBP Task Force on Atmospheric Chemistry and Climate; and on the cryosphere, polar research, and the International Polar Year (IPY).

International Geosphere-Biosphere Programme. IGBP, with its focus on the interactions between biological, chemical, and physical processes and human systems, contributes to CCSP Goals 1, 2, 4, and 5. The IGBP's core and joint projects involve a number of leading U.S. global change scientists. U.S. scientists are represented throughout the leadership of IGBP.

Key IGBP objectives for the coming year of substantive interest to the United States include finalization and publication of the science plan and implementation strategy for the next decade of IGBP research; planning for two integrative IGBP projects (the new project on Analysis, Integration, and Modeling of the Earth System and the second phase of the study of Past Global Changes); launching of a new ESSP cross-cutting study of global change and human health; further development and implementation of the Monsoon Asia Regional Study that will be carried out together with WCRP, IHDP, and DIVERSITAS; and expansion and improvement of IGBP's scientific contributions to efforts of the United Nations Commission on Sustainable Development and to the next IPCC assessment report.

International Human Dimensions Programme on Global Environmental Change. U.S. scientists play a lead role in planning and implementation of IHDP projects. IHDP develops and provides important inputs to CCSP efforts, including decision support as well CCSP Goals 1 and 5. IHDP held an Open Science Conference in 2005 that was attended by over 900 participants from across the globe and provided valuable input for the IHDP's development of a strategic plan and framework for its activities from 2007 to 2012. This plan is expected to call for expansion of South-North and South-South dialogs in order to more fully involve scientists from developing countries in IHDP and its individual projects.

IHDP intends in the coming year to introduce two new projects: a new IHDP core project on Urbanization and Global Environmental Change and a new cross-cutting Global Land Project, the latter to be co-sponsored by IGBP. IHDP will also play a major role in the new ESSP program on global change and human health. A new task force has been established to identify needs for and approaches to modeling related to the human dimensions of global change. IHDP is also working in conjunction with IGBP to implement the new phase of studies of land-ocean interactions in the coastal zone.

IHDP has also been involved in capacity building—for example, by hosting four training seminars involving 60 scientists and 20 trainers in conjunction with their Open Science Conference. IHDP is planning the 5th International Human Dimensions Workshop on the International Dimensions of Global Environmental Change that will focus on "Water, Trade, and the Environment" in October 2006 in Chiang Mai, Thailand.

DIVERSITAS. The DIVERSITAS program focuses on advancing the science of biodiversity, including quantification of biodiversity, the effects of global environmental change on biodiversity, and the effects of loss of biodiversity on ecosystem function. Through its activities, DIVERSITAS contributes to CCSP Goal 4, as well as other programs of high priority for the United States. U.S. scientists play an important role in developing and implementing DIVERSITAS research and syntheses.

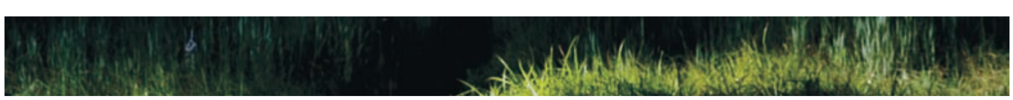
The DIVERSITAS scientific program is evolving and the program itself is just now maturing. DIVERSITAS convened an Open Science Conference in November 2005 that included 42 sessions and symposia and was attended by more than 600 participants from 60 countries, one-third of whom were from developing countries. DIVERSITAS was also involved in the preparations, especially in assembling the scientific program, for the international conference on "Biodiversity: Science and Government" held in January 2005 in Paris, which attracted about 2,000 participants from diverse sectors of society and from about 100 countries.

DIVERSITAS activities planned for the coming year that are of particular interest include the efforts of its bioDISCOVERY project that is directed to systematics, monitoring, and drivers of biodiversity change. Activities in this area are expected to contribute substantially to four of the specific elements of the GEOSS Work Plan.

The ecoSERVICES project is developing an agenda for the next generation of field experiments on the impacts of biodiversity changes on ecosystem functioning. Its bioSUSTAINABILITY project has convened a series of workshops and symposia directed at decisionmaking under uncertainty, urban bio-sustainability, and biodiversity measures for sustainable development in Southeast Asia.

In addition, DIVERSITAS is developing three new networks on biodiversity and agriculture, freshwater diversity, and biodiversity assessments in mountainous regions. DIVERSITAS is making major contributions to improving scientific input to the international Convention on Biological Diversity (CBD). Five new countries have joined the DIVERSITAS program over the past year and have contributed to the DIVERSITAS core budget.

SysTem for Analysis, Research and Training. The START program is sponsored by WCRP, IGBP, and IHDP, and seeks to establish regional networks of collaborating scientists and institutions in developing countries, thereby augmenting the capacity of those countries to conduct research on global change, including climate change. By establishing research networks and partnerships in developing countries, including areas where observations and data are sparse, the START program increases global capacity to conduct research on global change and thereby contributes to CCSP goals.



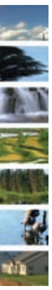
The United States continues to host the international START Secretariat in Washington, DC. START intends in the coming years to address the following challenges and developments in global change science:

- Moving beyond thematic/sectoral studies toward integrated regional studies that couple biophysical and human components; that coordinate observations, modeling, and process studies; and that address the two-way linkages between regional and global-scale change
- Promoting investigation of the biophysical impacts of urbanization (including the rise of mega-cities) and the effects of alternative development pathways on the carbon cycle
- Stimulating a second generation approach to impact assessment, with emphasis on vulnerabilities and risks posed by combined regional and global environmental change, which employs methods of risk assessment to better link science to policy formulation
- Acting to address the need for a vast increase in research-driven capacity building and research partnerships between science communities in the developed and developing world.

To this end, START plans over the coming year to:

- Initiate a new project on Advancing Capacity to Support Climate Change Adaptation that will involve as many as nine regional studies in developing areas of the world (with support provided by the European Union and the United Kingdom)
- Complete its program on Assessments of the Impacts of and Adaptations to Climate Changes, including preparation and submission of final reports to UNEP and the Global Environmental Facility
- Plan and convene its 2nd International Young Scientists' Conference to be held 7-8 November 2006, in Beijing, China, to immediately precede the ESSP Open Science Conference
- Convene a synthesis workshop in India on risk and vulnerability
- Convene an initial training session of an advanced study institute on water in the context of climate change
- Support capacity building for global change research in developing countries, especially in Asia and Africa.

Earth System Science Partnership. ESSP brings together researchers from diverse fields and across international boundaries to investigate multidisciplinary problems such as carbon, food, health, and water that cut across the objectives of its member programs. ESSP has established four joint projects: the Global Carbon Project, Global Environmental Change and Food Systems (GECAFS; see below), the Global Water System Project, and Global Change and Human Health. All of these programs draw from expertise of the U.S. scientific community and are expected to make substantive contributions to CCSP goals.



ESSP will convene its first Open Science Conference on 9-12 November 2006, in Beijing, China. The objectives of the conference are to:

- Present the results of the last 5 years of global environmental change research, emphasizing the Earth system science approach, in particular as it relates to ESSP joint projects on carbon, food, health, and water
- Highlight the variety of research conducted by the global environmental change community, particularly the core projects of the four international environmental change programs, and how that research contributes to and supports the objectives of ESSP
- Point the way for the next decade of Earth system science.

Themes selected thus far for the conference include:

- *Earth System Science Approach*. Advances in studies of the physical, biogeochemical, biodiversity, and human dimensions aspects of global environmental change
- *Integrated Regional Studies*. The dynamics, impacts, and consequences of the interactions between natural and social systems (including extreme events) at regional scales and how they connect with global-scale phenomena
- *Global Change in Monsoon Asia*. Global environmental change research in monsoon-affected areas of Asia
- *Science for Sustainability*. Global environmental change research relating to carbon, food, human health, and water as reflected in the ESSP joint projects.

The Global Environmental Change and Food Systems Project. GECAFS is an interdisciplinary research project spanning the natural and social sciences. It is developing a science agenda with direct inputs into policymaking. The new science agenda explicitly includes both how food systems could be adapted to cope with the impacts of global environmental change, and how different adaptation strategies could affect socioeconomic and environmental conditions. Of particular interest are possible feedbacks to the Earth system from efforts to improve food security relating to the dynamics of carbon, nitrogen, phosphorus, and water.

GECAFS brings together the agendas of global environmental change science and international development and will form partnerships between the environmental change research community and a broad range of other organizations, including national and international research bodies, national and international assessment units, national and regional civil society stakeholders and governmental authorities, intergovernmental organizations and United Nations agencies, and national and international donor agencies. This wide range of scientists and stakeholders working together will build upon and add value to the individual research agendas of the international environmental change research programs.

GECAFS' goal is to determine strategies to cope with global environmental change impacts on food systems and to assess environmental and socioeconomic

consequences of adaptive responses aimed at improving food security. This goal will be achieved by improved understanding of interactions between food systems and the Earth system's key socioeconomic and biogeophysical components. The research agenda will be specifically targeted toward delivering new information necessary to underpin policy formulation for improving food security in the face of global environmental change.

The long-term aims of GECAFS are to understand how global environmental change will affect food security in different regions and among different socioeconomic groups; to determine how different societies might adapt their food systems to cope with both global environmental change and changing demands for food; to assess how strategies designed to cope with global environmental change and changing demands for food will affect the environment, societies, and economies; and to provide information and research findings in formats that help improve policymaking for food systems in the context of global environmental change.

GECAFS aims to deliver a number of science-based products in the medium-term (3 to 5 years) to help achieve the long-term aims. GECAFS, which is a joint project of IGBP, IHDP, and WCRP, builds on ongoing ESSP research, helps set new ESSP agendas, and helps set IGBP, IHDP, and WCRP core project research in the broader context of economic development. This requires innovative research partnerships and, to this end, GECAFS has established formal research partnerships with the Consultative Group on International Agricultural Research, the United Nations Food and Agriculture Organization, and WMO. These partnerships are intended to help set a precedent for formal collaboration between science and development agendas in environmental change research to mutual benefit. It also raises the priority of environmental change issues in development agencies.

Inter-American Institute for Global Change Research. IAI is an intergovernmental treaty organization established in 1994 to promote collaborative research on global change in the Americas. IAI encourages hemispheric collaboration on projects that would otherwise not be possible, and has developed a rigorous scientific review process for proposals it receives. IAI requires every project to be a closely integrated effort of physical and social scientists so that projects, in addition to undertaking research on important scientific issues, provide information for local, national, and/or regional decisionmakers.

From among over 30 IAI networks, a network focused on "biogeochemical cycles under land-use change in the semi-arid Americas" was formed between research institutions in Argentina, Brazil, Canada, Mexico, and Venezuela which provides an example of the type of work typically carried out with IAI support. This network integrates biogeochemical and socioeconomic data at the farm and regional scales within different land-use and soil management systems in order to evaluate and predict regional changes in resource quality. Often, information resulting from global change research does not reach rural communities; however, this IAI network successfully distributed scientific information to farmers within the study regions (municipalities) and supported predictions at a regional scale. Several national extension service bulletins included recommendations for soil management and conservation developed during this project.

The network's researchers participated in the consultant group for the new Argentine provincial soil conservation law that was passed in 2004, and the Provincial Secretary for the Environment made use of network-generated publications to raise consciousness about soil degradation in agricultural and natural ecosystems. In Mexico's Yucatan Peninsula, the network studied the decline of corn productivity after the second year of cultivation, and determined that corn production can be maintained with the use of cover crops and green manures. The Mexican state government adopted these recommendations as a formal policy.

The network found that the removal of native vegetation for establishment of pastures or agricultural fields in the study areas of northeastern Brazil and the La Pampa area of Argentina consistently led to severe decreases in soil fertility. The increasing area of cash-crop production in Argentina caused higher stocking rates in the savanna ranching region, with farmers moving their cattle to less productive regions while intensifying agricultural production in more humid regions. This phenomenon caused overstocking and overgrazing of natural grasslands and depletion of soil carbon.

The network developed a spatially explicit land-use model for agricultural ecosystems in northeastern Brazil and the La Pampa area of Argentina that takes into account varying climatic scenarios. The network developed an indicator of soil degradation and productive potential that is being used for soil management recommendations as well as for land-use policy decisions on a regional scale. The network also identified strong competition for water between trees and crop species, and proposed the adoption of other agroforestry practices to avoid competitive interactions. Understanding of the relationship between the quality of organic fertilizer available within the farms, nitrogen mineralization, and synchronization to crop demand allowed fertilization practices that increased crop productivity up to 300%.

International Cooperation in Observing Systems

Group on Earth Observations. On 31 July 2003, 33 nations plus the European Commission adopted a declaration that signifies political commitment to move toward development of a comprehensive, coordinated, and sustained Earth observation system. The Earth Observation Summit was hosted by three Cabinet Secretaries and attracted a distinguished group of ministers and other dignitaries from around the world who were committed to significantly advancing our collective ability to gather and apply Earth observation data.

Summit participants affirmed the need for timely, quality long-term global information as a basis for sound decisionmaking. In order to monitor continuously the state of the Earth, to increase understanding of dynamic Earth processes, to enhance prediction of the Earth system, and to further implement environmental treaty obligations, participants recognized the need to support the creation of a comprehensive, coordinated, and sustained Earth observing system of systems.

To further this goal, Summit participants launched the intergovernmental *ad hoc* Group on Earth Observations (GEO) to develop a 10-Year Implementation Plan. At the third Earth Observation Summit in Brussels, Belgium, on 16 February 2005, ministers from almost 60 countries and the European Commission established GEO on a long-term basis to take the steps necessary to implement GEOSS. Participants endorsed the GEOSS 10-Year Implementation Plan, which describes collective targeted actions for establishing GEOSS, and stated their intention to provide the support necessary to execute the plan.

The first meeting of the newly established GEO took place in May 2005, at which China, the European Commission, South Africa, and the United States were selected as GEO Co-Chairs and an Executive Committee was created to facilitate and implement decisions of the GEO Plenary between meetings. At its second plenary-level meeting in December 2005, GEO formally established committees and agreed to embark on an ambitious 2006 work plan that encompasses all nine societal benefit areas (see Figure 46) identified in the GEOSS Implementation Plan.

Figure 46: GEO Societal Benefits Focus. This illustration highlights the areas of societal benefit identified in the GEOSS Implementation Plan. *Credit: U.S. Group on Earth Observations.*

While GEOSS benefits the climate community, it also addresses a wide range of other priority applications—for example, agricultural management, biodiversity, disasters, ecosystems, energy resources, health, water, and weather. GEO currently includes 60 countries and the European Commission, as well as 43 international organizations.

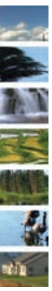
Selected International Assessments and Decision-Support Programs

Sector Applications Research Program. The Sector Applications Research Program (SARP) seeks to bridge the gap between science and decisionmaking through the focused creation, dissemination, and exchange of climate-related research findings critical for understanding and addressing resource management challenges in vital social and economic sectors (e.g., coastal and water resources, agriculture, health).

SARP fosters decision-support research and applications activities that link science and technology to economic development, sustainable management needs, and policymaking processes. The program builds upon a 10-year NOAA endeavor in human dimensions research and climate research applications, and recent advances in research, assessment, and decision-support systems for climate and global change.

The programs from which SARP evolved entailed international activities that advanced the use of science in decisionmaking, such as Regional Climate Outlook Forums, interdisciplinary human dimensions research, pilot applications projects, workshops, training sessions, capacity building, and technical assistance in Africa, Southeast Asia, Latin America and the Caribbean, and the Pacific. Partners included the World Bank, WMO, USAID, IRI, and regional institutions in Africa, Latin America and the Caribbean, Southeast Asia, and the South Pacific. In the coming year, SARP will continue to build upon and expand these partnerships and activities as appropriate, including the funding of targeted applications research activities in key sectors (e.g., water resources, coastal management).

Arctic Climate Impact Assessment. The full underlying scientific document was published as planned at the end of 2005. The 1,042-page scientific report stands as the most comprehensive document to date addressing the state of the Arctic climate. It will serve the scientific and policy communities as an important reference on Arctic climate, its changes, and potential impacts. The report is available for download from the ACIA Secretariat (<www.acia.uaf.edu/pages/scientific.html>) and for purchase from Cambridge University Press.



Millennium Ecosystem Assessment. The technical volumes of the Millennium Ecosystem Assessment—a $21 million, four-year effort involving 1,500 of the world's leading scientists—were released on 19 January 2006. These are the working group reports that examine Current State and Trends, Scenarios, Policy Responses, and Multi-Scale Assessments. A summary for decisionmakers of the four technical volumes was also released. These reports should advance natural resource management by providing peer-reviewed, policy-relevant information to decisionmakers in the government and the private sector. This information is of high relevance to a variety of international ecosystem-related conventions, including the CBD.

International Research Institute for Climate and Society. In October 2005, the Trustees of Columbia University added "Society" to IRI's name to better reflect the work of the Institute. The mission of IRI is to enhance society's capability to understand, anticipate, and manage the impacts of seasonal climate fluctuations, in order to improve human welfare and the environment, especially in developing countries. IRI's international efforts involve research in climate prediction, monitoring, and analysis targeted to address problems of climate risk in agriculture and food security; water resources; public health; disasters; and cross-cutting issues such as drought management. A combination of scientific rigor, problem-centered analysis, and partner teamwork is beginning to yield successful approaches to climate risk management.

IRI has several ongoing projects in Africa, Asia, and Latin America. Many of these projects will continue in FY 2007. These include implementing an agricultural pilot project in the Southern Province of Zambia as part of the WMO implementation of the USAID project for Southern Africa; development of user-friendly climate information for the malaria control service and support for the operation of integrated Malaria Early Warning Systems in South Africa; linking climate forecasts with crop simulation models to predict field-scale maize yields at sites in southern Kenya and southern Zambia; incorporating climate forecasts into season-ahead decisionmaking on rice imports in Indonesia; and research on the impact of droughts on livelihoods in Rajasthan, India.

In addition, IRI has launched an effort to raise institutional and societal awareness of climate vulnerability and risk as an arena for action. IRI initiated institutional and policy research at two demonstration sites in Southeast Asia through a framework of collaborative research programs with two key socioeconomic research institutes in the region. The Angat Reservoir in the Philippines supplies water for Manila, and provides water for irrigation and hydropower needs. IRI is studying the institutional setting and decisionmaking process for the Angat Reservoir to explore opportunities to use climate forecasts of streamflow to improve management of limited water resources. In Nusa Tenggara Timur, Indonesia, IRI has undertaken institutional and policy research to understand the dynamics and decisionmaking related to food security in this remote and poor province of Indonesia, which experiences highly variable rainfall.

Intergovernmental Panel on Climate Change. The U.S. Government is the leading contributor to the IPCC and has played an active role in the IPCC process since its inception. The United States currently chairs IPCC's Working Group I (which focuses on the physical basis of climate change) and provides support for its Technical Support Unit (TSU).

In FY 2005, the Working Group I TSU played a lead role in the coordination and publication of a Special Report on Ozone and Climate (SROC), entitled *Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons*. The report covers scientific aspects of ozone-depleting substances and their substitutes as they pertain to radiative forcing, as well as issues involved in addressing atmospheric emissions of these substances. The Summary for Policymakers was approved and the underlying report accepted in April 2005. A Special Report on Carbon Capture and Storage (SRCCS), overseen by the Working Group III TSU in he Netherlands, was approved and accepted in September 2005. On behalf of DOS, CCSP coordinated the U.S. Government review of the SROC, including the final concurrence check of the summary documents. CCSP assisted the CCTP with like responsibilities for the SRCCS. Both reports involved extensive participation from U.S. scientists and technical experts.

The IPCC is now focusing all effort on development and production of its Fourth Assessment Report (AR4). CCSP supports participation of experts to serve as Coordinating Lead Authors, Lead Authors, and Review Editors, and to participate in workshops that contribute to the IPCC process. At present, 79 U.S. scientists serve as AR4 authors and 14 as Review Editors.

During FY 2006, first drafts were revised taking into consideration the very large number of comments received during the staggered Expert Reviews (held from September to November 2005 for Working Groups I and II, and November 2005 to January 2006 for Working Group III). CCSP coordinated the U.S. Government review of the second drafts of the Working Group I and II contributions to AR4 (April to June 2006 for Working Group I and May to July 2006 for Working Group II) and CCTP coordinated the U.S. Government review of the second draft of the Working Group III contribution (July to September 2006). IPCC authors are using government and expert inputs to prepare a final draft by late 2006. CCSP and CCTP also will be involved in the review of the respective Summaries for Policymakers and Technical Summaries. All working group contributions to the AR4 are expected to be completed by May 2007.

The North American Regional Climate Change Assessment Program. The North American Regional Climate Change Assessment Program (NARCCAP) is part of a U.S.-Canadian-European collaborative regional climate modeling study. NARCCAP joins, as a new U.S. and Canadian component, the EU Prediction of

Regional scenarios and Uncertainties for Defining European Climate Change Risks and Effects project. NARCCAP's primary objective is to develop, and make openly available, multiple high-resolution regional climate change scenarios for use in impact and risk assessments.

Analyses of the scenarios, with a focus on North America, will be conducted in FY 2007 in order to understand critical regional climate change issues, such as the effects of increased greenhouse gases on the frequency of various types of extreme weather events; to enhance understanding of key issues in regional climate modeling, including methodological approaches; to conduct a limited examination of uncertainties in projections of future regional climate by regional and global climate models; and to create greater collaboration between U.S., Canadian, and European climate modeling groups to leverage the diverse modeling capability across these nations.

Famine Early Warning System Network. The efforts of USAID's Famine Early Warning System Network (FEWS NET) to provide short- and long-term climate forecasting in the developing world is helping to enhance the adaptive capacity of developing countries to climate variability and change. For instance, in August 2005, FEWS NET released a report, *Recent Drought Tendencies in Ethiopia and Equatorial Subtropical Eastern Africa*, that demonstrated how warming in the Indian Ocean and changes in the monsoonal circulation pattern could reduce rainfall across large areas of the Greater Horn of Africa. This information will allow development agencies and regional and local institutions to direct appropriate resources and support toward strengthening the adaptive capacity of affected groups and the food production systems upon which they depend. This work relates closely to CCSP Goal 5, focus 5.2.

Radio and Internet for the Communication of Hydro-Meteorological and Climate Information for Development. The USAID Office of Foreign Disaster Assistance and NOAA have supported the Radio and Internet for the Communication of Hydro-Meteorological and Climate Information for Development (RANET) program in order to improve remote community access to and use of hydro-meteorological and climate information such as forecasts, observations, and warnings. RANET is an international collaboration of meteorological services and nongovernmental partners to develop communication tools and networks appropriate for rural and resource-poor communities. The program integrates a variety of satellite- and terrestrial-based communication technologies, and the networks RANET establishes help national agencies receive critical information from regional and international partners. These networks also enable national meteorological services and related agencies to disseminate their own information to remote communities in their country. RANET currently works in Africa, Asia, and the Pacific (see <www.ranetproject.net>).

Bilateral Cooperation in Climate Change Science and Technology

In June 2001, President Bush committed the United States to developing with our international partners an effective and science-based response to the issue of climate change. Today the United States remains committed to working with others, including both developed and developing country partners, to promote cooperative and collaborative approaches to address the global challenge of climate change.

To that end, DOS is leading a major interagency effort to advance international cooperation in climate change science and technology. Since June 2001, the United States has launched bilateral climate partnerships with 15 countries and regional organizations that, combined with the United States, account for almost 80% of global greenhouse gas emissions. Partnerships have been established with Australia, Brazil, Canada, China, Central America (Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama), the European Union, Germany, India, Italy, Japan, Mexico, New Zealand, Republic of Korea, Russian Federation, and South Africa. These bilateral initiatives seek to build on key elements of CCSP and CCTP, including research, observations, data management and distribution, and capacity building.

Substantive project-level work plans are now in place with each of these countries. Successful joint projects have been initiated in areas such as climate change science; clean and advanced energy technologies; carbon capture, storage, and sequestration; and policy approaches to reducing greenhouse gas emissions. The United States is also assisting key developing countries in efforts to build the scientific and technological capacity needed to address climate change.

Over the coming year, two key objectives for the bilateral activities will be continued advancement of results-oriented programs and the fostering of substantive policy dialogs within all 15 of the bilateral climate change partnerships. In order to broaden U.S. cooperative efforts to advance a practical and effective global response to climate change, the United States will expand outreach and support to the developing country community, utilizing a regional approach where feasible.

U.S.-India Bilateral Stakeholder Meeting. EPA sponsored a stakeholder workshop in India to bring together U.S. and Indian researchers and decisionmakers to examine possible adaptation strategies for coping with climate change, variability, and natural disasters. The project grew out of the initiation of the U.S.-India climate bilateral agreement. The workshop constitutes the contribution of the EPA's Office of Research and Development to the U.S. Government's climate bilateral activities with

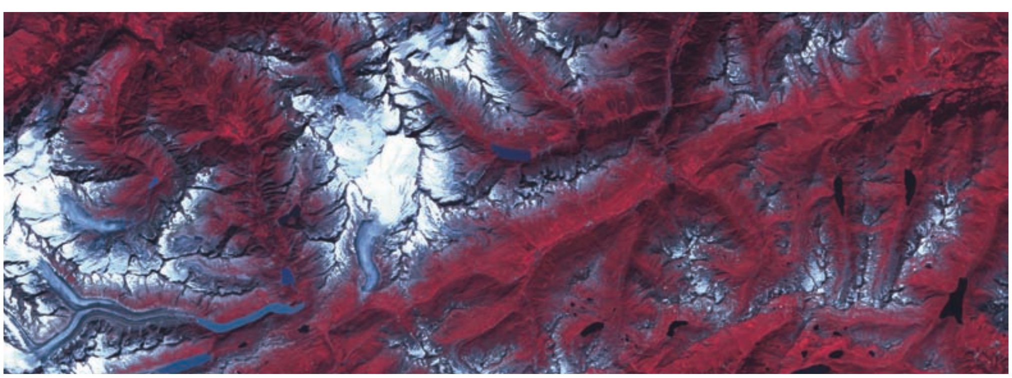
India. EPA and NOAA have the lead within CCSP for research on the impacts of climate change and on adaptive response.

The workshop was held in New Delhi on 5-7 January 2006, and brought together stakeholders from the science and management communities to engage in information-sharing on the effects of, and anticipatory adaptation to, climate change and variability; to develop an understanding of the roles and responsibilities among various government and nongovernmental actors in the area of adaptation to climate variability and disaster response; and to develop specific recommendations for further investigations by Indian researchers and for pilot implementation activities.

Additional Climate-Related International Activities

International Polar Year. IPY will be an intense, coordinated campaign of polar observations, research, and analysis that will be multidisciplinary in scope and international in participation. IPY will use today's powerful research tools, such as high-powered computers, automated observatories, satellite-based remote sensing, autonomous vehicles, and genomics, to better understand the key roles of the polar regions in global processes. IPY 2007-2008 will be fundamentally broader than the IPYs held in 1882-1883 and 1932-1933 or the International Geophysical Year of 1957-1958. This IPY will explicitly incorporate multidisciplinary and interdisciplinary studies, including biological, ecological, and social science elements.

A goal of IPY 2007-2008 is to undertake projects that any single nation could not normally achieve. The polar regions—both the Arctic and the Antarctic—are inherently international terrain, both because of the many nations who share these regions and because what happens in these regions affects nations around the globe. The science challenges we face far exceed the capability of any one nation, so international collaboration is expected to be a key component of IPY projects. It is hoped that the



international collaborations started during IPY will build relationships and understanding that will bring long-term benefits.

IPY also provides an opportunity to think beyond traditional disciplinary constraints toward a new level of integrated, cooperative science. In addition, IPY will serve as a mechanism to attract and develop a new generation of scientists and engineers with the versatility to tackle complex global issues. IPY is an opportunity to organize an exciting range of education and outreach activities designed to excite and engage the public, with a presence in classrooms around the world and in the media in varied and innovative formats.

The International Group of Funding Agencies for Global Change Research. The United States, through its membership in the International Group of Funding Agencies for Global Change Research (IGFA), engages representatives from 20 national funding agencies with responsibility for funding global change research in discussions related to funding climate and global change research. Through annual plenary meetings, regular steering committee and staff group meetings, and other activities, member agencies regularly exchange information and views regarding global change research programs, new initiatives, research infrastructure, and related issues.

Topics of mutual interest are identified and solutions determined and implemented through the relevant national processes, and, in some cases, through coordinated international efforts. One such topic that IGFA is currently addressing is the connection between global environmental change and development-oriented research. The United States has chaired IGFA for the past 2 years.

The Atmospheric Brown Cloud Program. U.S. scientists are participating in an initial field experiment this year centered around the Maldivian Atmospheric Brown Cloud Program observatory, which is co-funded by NSF, NOAA, NASA, and the Government of the Maldive Islands. If successful, this Maldives Autonomous Unmanned Aerial Vehicles (AUAV) Campaign will be the first time three AUAVs are flown simultaneously above, within, and below clouds in a polluted environment (the Indian Ocean) to collect concurrent aerosol and cloud microphysical data, aerosol chemistry data, meteorological data, and radiation data so that the indirect effect of aerosols on cloud radiative properties can be calculated. Scientists expect to analyze the field data in 2007.

African Network of Earth System Science. Building on the success of its September 2005 workshop assessing needs and opportunities for regional cooperation on global change research, the African Network of Earth System Science (AFRICANESS) intends to provide a regional platform for the study of global environmental change. This has the objective of enabling African scientists to communicate more effectively and set priorities and agendas for research in Africa. It will also allow African scientists to better coordinate and communicate with the rest of the world. An organizing committee with extensive regional representation has been established. In its initial efforts, AFRICANESS will focus on water and climate modeling, desertification, land degradation, biodiversity and food security, health and pollution, and marine ecosystems.

APPENDIX
The Climate Change Science Program Participating Agencies

APPENDIX

THE CLIMATE CHANGE SCIENCE PROGRAM PARTICIPATING AGENCIES

The following pages present information about the contributions to the CCSP of each of the program's participating agencies:

- Department of Agriculture (USDA)
- Department of Commerce / National Oceanic and Atmospheric Administration (DOC/NOAA)
- Department of Defense (DOD)
- Department of Energy (DOE)
- Department of Health and Human Services (HHS)
- Department of the Interior / U.S. Geological Survey (DOI/USGS)
- Department of State (DOS)
- Department of Transportation (DOT)
- Agency for International Development (USAID)
- Environmental Protection Agency (EPA)
- National Aeronautics and Space Administration (NASA)
- National Science Foundation (NSF)
- Smithsonian Institution (SI).

Principal Areas of Focus, Program Highlights for FY 2007, and Related Research are summarized for each agency.

U.S. DEPARTMENT OF AGRICULTURE

Agricultural Research Service (ARS)
Cooperative State Research, Education, and Extension Service (CSREES)
Economic Research Service (ERS)
Forest Service (FS)
Natural Resources Conservation Service (NRCS)

Principal Areas of Focus

USDA conducts and sponsors a broad range of research that supports the CCSP. Areas of emphasis include evaluating environmental changes that pose risks to natural resources, forestry, and agriculture; assessing their likelihood, consequences, and potential responses; estimating the contribution of forestry and agricultural activities as drivers of environmental change; identifying processes that can be managed; and developing approaches in which agriculture and forestry can help reduce net greenhouse gas emissions. USDA's research program seeks to determine the significance of terrestrial systems in the global carbon cycle, to promote the capture and use of methane emitted from livestock waste facilities for on-farm power generation, to assess the potential of bioenergy as a substitute for fossil fuels, to identify agricultural and forestry activities that can help reduce greenhouse gas concentrations and increase carbon sequestrations, to quantify the risks and benefits arising from environmental changes to agricultural lands and forests, and to develop management practices that can adapt to the effects of global change, including potential beneficial and adverse effects. USDA is the lead agency responsible for preparing CCSP Synthesis and Assessment Product 4.3, "The Effects of Climate Change on Agriculture, Biodiversity, Land, and Water Resources." USDA intends to complete production of this report by the end of 2007. USDA is also partnering with other agencies on other synthesis and assessment products identified in the *CCSP Strategic Plan*. For example, USDA agencies have contributed substantially to the development of Synthesis and Assessment Report 2.2, "North American Carbon Budget and Implications for the Global Carbon Cycle."

Program Highlights for FY 2007

ARS's national program on global change continues to address carbon cycle and carbon storage, trace gas emissions and sinks, impacts of environmental changes on agricultural systems, and feedbacks among agricultural systems, weather systems, and the water cycle. A focus of the program is building a scientific knowledge base that will enable producers, land managers, and strategic decisionmakers to adapt to climate change, and to mitigate contributions of agricultural systems to factors contributing to climatic change. Infrastructure to measure greenhouse gas emissions from different tillage systems at different locations across the country will continue gathering data that will provide insights into agricultural greenhouse gas emissions and into soil carbon sequestration. The effects of elevated atmospheric carbon dioxide on plants will continue to be investigated, as will the hydrological response to climate change, such as drought, that may affect soil water availability for agriculture and other water supplies. Environmentally friendly and economically feasible alternatives to the use of stratospheric ozone-depleting methyl bromide are being developed as a treatment to control pests. ARS will continue to help develop and take note of guidance offered by interagency working groups to ensure that research provides relevant and significant contributions to the understanding of global change and its impact on the Nation's ability to produce food and fiber and to protect natural resources.

CSREES continues to support the USDA Ultraviolet-B Monitoring and Research Network Program. This program provides information on the geographical distribution and temporal trends of UV-B radiation in the United States. This information is critical to the assessment of potential impacts of increasing ultraviolet radiation levels on agricultural crops and forests. The program consists of both a research and climatological network. The research network provides state-of-the-art, high-resolution spectroradiometers to six sites, with cross-disciplinary use of the data. The climatological network uses less sophisticated instrumentation and will eventually total between 30 to 40 monitoring stations. Sites included in the research network enhance opportunity for collaborative research, and provide calibration benchmarks for the USDA climatological network as well as other CCSP agency ultraviolet radiation research efforts. CSREES continues to support global change research through the National Research Initiative (NRI) Competitive Grants Program and formula-funded programs. NRI includes programs for carbon and nutrient cycles, air and water quality, land-use and -cover change, ecosystems, agricultural waste management, and invasive species research—spanning forest, rangeland, and agricultural ecosystems. Formula funds received through the Hatch and McIntire-Stennis Acts fund climate-related research at the land-grant universities and colleges and at multi-state institutions and state agricultural research experiment stations. CSREES is using the *CCSP Strategic Plan* in formulating priorities under the NRI program and in shaping specific grant announcements for research, education, and extension projects.

Forest Service research is (i) expanding understanding of the global carbon cycle in forest and rangeland ecosystems, and the consequences and feedback from the management and use of these ecosystems as they interact with the atmosphere; (ii) improving accuracy and ease of analyses of U.S. forest carbon inventory, and other monitoring and analysis systems for carbon dioxide; (iii) enhancing understanding of climate variability on plant species migration on forests and rangelands; (iv) enhancing understanding of climate change impacts on forest health; (v) accelerating the development and deployment of management systems that reduce and mitigate greenhouse gas emissions and sequester carbon in cost-effective and environmentally beneficial ways; (vi) integrating observation and monitoring networks with process studies to better understand, forecast, and manage relationships between forest and rangelands and climate; (vii) accelerating the development of management technologies to increase carbon sequestration, provide fossil fuel offsets, enhance productivity, and maintain environmental quality; and (viii) providing integrated prediction models of forest carbon dynamics. Active forest management can enhance carbon sequestration by increasing the removal rate of carbon dioxide from the atmosphere and by storing carbon in living biomass, soil, litter, dead wood, and wood products, in addition to other benefits. Critical outcomes of this research include accelerated development, demonstration, and deployment of management systems that reduce and mitigate greenhouse gas emissions and sequester carbon in a cost-effective and environmentally sound manner.

Related Research

USDA remains active in the Climate Change Technology Program (CCTP) and related research efforts. The Forest Service, NRCS, ARS, CSREES, and the Rural Development mission area support improved measurement and accounting of greenhouse gases from agriculture and forestry systems, as well as energy initiatives and renewable energy systems such as biofuels and biomass-related research and development. NRCS and the Forest Service are cooperating in development of web-based assessment tools for agricultural producers to account for benefits accruing on carbon fluxes and greenhouse gas emission from conservation practices. In addition, NRCS and the Forest Service are developing new measurement technologies, analytical techniques, and information management systems related to spatial carbon distributions. USDA also is filling gaps in ecosystem information by continuing to collect data on land use, resource conditions, and climate through the National Resources Inventory, the Forest Inventory and Analysis Program, the Soil Climate Analysis Network, and the Snowpack Telemetry system. These networks provide critical data needs on the status and condition of land use in the United States in support of CCSP research.

DEPARTMENT OF COMMERCE / NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Principal Areas of Focus

NOAA's climate mission is: "To understand and describe climate variability and change to enhance society's ability to plan and respond." This is an end-to-end endeavor focused on providing decisionmakers a predictive understanding of the global climate system and to "translate" data so the public can incorporate the information and products into their decisions. These outcomes are achieved through implementation of a global observing system, focused research to understand key climate processes, improved modeling capabilities, and the development and delivery of climate information services. Specific objectives follow:

- Describe and understand the state of the climate system through integrated observations, analysis, and data stewardship
- Reduce uncertainty in the information on atmospheric composition and feedbacks that contribute to changes in Earth's climate
- Provide climate forecasts for multiple time scales to enable regional and national managers to better plan for the impacts of climate variability, and climate assessments and projections to support policy decisions with objective and accurate climate change information
- Understand and predict the consequences of climate variability and change on marine ecosystems
- Provide information and tools to support decisionmakers in improving management of risks to the U.S. economy in sectors and areas that are sensitive to impacts from weather and climate.

NOAA relies on its Federal, academic, private, and international partners to achieve its objectives. These objectives are implemented through five distinct, yet integrated, programs: Climate Observation and Analysis, Climate Forcing, Climate Predictions and Projections, Climate and Ecosystems, and Regional Decision Support.

Program Highlights for FY 2007

Observations and Analysis

The objective of the Climate Observations and Analysis (COA) Program is to describe and understand the state of the climate system through integrated observations, data management, and analysis. The COA Program is organized under three capabilities: Observations (atmosphere and oceans, including the Arctic), Data Management, and Analysis of the Climate System. These capabilities taken together increase the value and utility of observations, improve the performance of models, and reduce the uncertainty of predictions. A major objective of the COA Program is to contribute to the national and global objectives outlined in the *Strategic Plan for the Climate Change Science Program*, as well as NOAA's Strategic Plan and the Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan.

Activities in FY 2007 will:

- Reduce uncertainties in sea-level change, sea surface temperature, and estimates of changes in the carbon inventory in the global ocean

- Document the ocean's heat storage and transport, and changes in the ocean's contributions to the global water cycle
- Via aircraft, deploy drifting data buoys in the path of approaching hurricanes to measure the ocean's heat energy potential
- Assess and address the impact on the climate observing system of changes in the future National Polar-Orbiting Operational Environmental Satellite System (NPOESS)
- Retrofit the Global Climate Observing System (GCOS) Upper Air Network sites in developing nations and continue serving as the GCOS Lead Center for the GCOS Surface Network
- Working with Canada, deploy an atmospheric observatory in northeastern Canada to provide high-resolution characterization of clouds and aerosols, and of incoming and outgoing radiation
- Collect data to understand changes in the temperature and salinity structure of the ocean beneath sea ice, and the biotic response to physical changes (rapid warming and diminished ice cover)
- Implement the "Near-Term Opportunities" outlined in the U.S. Group on Earth Observations' Strategic Plan—that is, disaster warning, global land cover, sea level, drought, air quality, and enhanced data management.

Climate Forcing

The objective of the Climate Forcing Program is to better quantify the information on atmospheric composition and feedbacks that contribute to changes in Earth's climate. Specifically, the program seeks to provide the understanding needed to link "emissions" to the "radiative forcing of climate change" for science-based decision support. The Climate Forcing Program is providing research (i) to understand atmospheric and oceanic processes, both natural and human-related, that affect carbon dioxide trends; (ii) to quantify the climate roles of the radiatively important trace atmospheric species such as fine-particle (aerosols), ozone, and chemically active greenhouse gases; and (iii) to understand and assess stratospheric ozone depletion. Research may be directly applied to climate projection and to policy decisions regarding carbon management, and provides timely and adequate information needed to broaden the suite of non-carbon options for addressing changes in climate forcing.

Activities in FY 2007 will:

- Contribute to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and the international assessment regarding the depletion of the ozone layer
- Involve participation in a multi-institutional intensive field program that will investigate scientific questions common to both climate and air quality (i.e., the Gulf of Mexico Atmospheric Composition and Climate Study)
- Analyze ozone profiles measured across mid-latitude North America during a 2004 climate field study, with the aim of estimating how much ozone is formed over the continent in the summer
- Investigate aerosol distributions and their warming and cooling effects via the Oklahoma City Field Study, planned for the summer of 2007
- Continue the carbon atmospheric observing system across the Nation in support of research to reduce uncertainty in U.S. carbon sources and sinks
- Continue to develop and test methods for regional and continental estimates of carbon sources and sinks via an intensive field investigation centered on the mid-continent region of North America
- Continue to re-measure key ocean properties along cross-sections in the South Atlantic and North Pacific that were last measured in 1989 and 1991, respectively, via the Repeat Hydrography Program
- Design new sensors to measure carbon dioxide exchange across the air-sea interface for use on autonomous platforms such as floats, gliders, surface drifters, and autonomous underwater vehicles.

Predictions and Projections

The objectives of the Climate Predictions and Projections Program are to provide climate forecasts for multiple time scales to enable regional and national managers to better plan for the impacts of climate variability, and to provide climate assessments and projections to support policy decisions with objective and accurate climate change information. This program provides the Nation with a seamless suite of environmental forecasts (i.e., outlooks and projections) on intraseasonal, seasonal, interannual, and multidecadal time scales and on regional, national, and global spatial scales. The global environment includes not only the atmosphere, hydrosphere, cryosphere, biosphere, and lithosphere, but also land/ocean biogeochemical processes, ecosystems, atmospheric chemistry, and air quality. To achieve its objectives, this program maintains a suite of operational climate outlooks and strives to implement the next-generation operational climate outlooks and assessments by improving climate models, improving forecast generation techniques, and maintaining real-time climate monitoring data sets.

Activities in FY 2007 will:

- Address significant uncertainties associated with the water cycle through a study that comprehensively addresses the water budget within DOE's Atmospheric Radiation Measurement Program Southern Great Plains site
- Hone advanced ensemble multi-model prediction techniques for surface and subsurface hydrological parameters, with the objective of transferring or transitioning the improved techniques for operational application in the seasonal/interannual time scale
- Continue research on extended drought causes via monitoring, analysis, prediction, and support to drought information systems such as the National Integrated Drought Information System
- Build upon results from the 2006 African Monsoon Multidisciplinary Analysis campaign.

Climate and Ecoystems

The objective of the Climate and Ecosystems Program is to understand and predict the consequences of climate variability and change on marine ecosystems. The program accomplishes this by coupling observations with information from retrospective and process studies in order to detect the impacts of climate on marine ecosystems and build an understanding of climate-ecosystem relationships. The goal of the program is to develop forecasts of changes in fishery, coastal, and coral reef resources in response to climatic changes. The forecasts provide users and managers of ocean and coastal resources the information they require to adapt to changing climate regimes. In FY 2007, a collaborative research program will synthesize field and model information in the Northeast Pacific to better understand and predict responses of these ecosystems to climate change.

Regional Decision Support

The Regional Decision Support (RDS) Program provides information and tools to support decisionmakers in improving management of risks to the U.S. economy—and taking advantage of opportunities—in sectors and areas that are sensitive to impacts from weather and climate. Effective incorporation of climate information provides decisionmakers with the data, analysis, and new knowledge that can help them achieve the best possible outcome with regard to a varying climate. This includes the socioeconomic effects of drought, El Niño and La Niña events, sea-level rise, and other high-impact climate events. RDS addresses an increased demand for traditional climate services, such as data and forecast dissemination and customer support, as well as identifying and satisfying new requirements for decision support in sectors such as water, fire, emergency preparedness, health, transportation, energy, coastal, urban, and ecosystem management. Demand for increased services is met through research into decisionmaker needs and prototype product development, transition of research products into application and operations, and operational delivery and support of climate services.

Activities in FY 2007 will:

- Produce the following CCSP synthesis and assessment products slated for publication in 2007
  - "North American Carbon Budget and Implications for the Global Carbon Cycle" (2.2)
  - "Aerosol Properties and Their Impacts on Climate" (2.3)
  - "Climate Projections based on Emissions Scenarios for Long-Lived Radiatively Active Trace Gases and Future Climate Impacts of Short-Lived Radiatively Active Gases and Aerosols" (3.2)
  - "Best-Practice Approaches to Characterize, Communicate, and Incorporate Scientific Uncertainty in Decisionmaking" (5.2)
  - "Decision Support Experiments and Evaluations using Seasonal to Interannual Forecasts and Observational Data" (5.3)
- Launch "Coping with Drought through Research and Regional Partnership" as a new effort to analyze the social and economic impacts of drought, and the use of climate information in drought planning
- Transfer research to applications through a competitive program that supports proposals for transitioning experimentally mature climate tools, methods, and processes from research to sustained operational delivery of useful climate information, products, and services to local, regional, national, and international decisionmakers and policymakers.

Related Research

In addition to focused CCSP efforts, related activities include coastal and coral reef resources in response to climatic changes in oceanic water mass distributions, sea-surface temperature, sea-level rise, and coastal runoff; enhanced prediction and observation systems in support of weather and seasonal to interannual climate forecasts; determination of long-term changes in temperature and precipitation over the United States through long-term (50+ years) operation of the U.S. Climate Reference Network; continued buildout of the Comprehensive Large-Array Storage System to meet the growth in observational data from satellite and radar systems; and dissemination of global change information.

DOC's National Institute of Standards and Technology (NIST) provides measurements and standards that support accurate and reliable climate observations. NIST also performs calibrations and special tests of a wide range of instruments and techniques for accurate measurements. NIST provides a wide array of data and modeling tools that provide key support to developers and users of complex prediction models.

DEPARTMENT OF DEFENSE

Principal Areas of Focus

The Department of Defense—while not supporting dedicated global change research—continues a history of participation in the CCSP through sponsored research that concurrently satisfies national security requirements and stated goals of the CCSP. All data and research results are routinely made available to the civil science community. DOD science and technology investments are coordinated and reviewed through the Defense Reliance process and published annually in the *Defense Science and Technology Strategy*, the *Basic Research Plan*, the *Defense Technology Area Research Plan*, and the *Joint Warfighting Science and Technology Plan*.

Program Highlights for FY 2007

Satellite Sensors and Observations

DOD will fund 50% of the National Polar-Orbiting Operational Environmental Satellite System (NPOESS), as a result of the convergence of national sensing suites. NPOESS will monitor global environmental conditions, and collect and disseminate data related to weather, atmosphere, oceans, land, and near-space environment. The NPOESS Program is managed by the tri-agency Integrated Program Office run by DOC, DOD, and NASA.

Global Observations and Models

The Navy is a principal member of the National Oceanographic Partnership Program, incorporating the Integrated Ocean Observing System and associated data management and communications, the Global Ocean Observation System, the Global Ocean Data Assimilation Experiment (GODAE), and the National Federation of Regional Associations (<http://www.ocean.us/> and <http://usnfra.org>). This broad partnership of institutions collaborates in the development and demonstration of integrated ocean observations systems, data management systems, and eddy-resolving, real-time global and basin-scale ocean prediction systems. As part of GODAE, the Hybrid Coordinate Ocean Model (HYCOM) runs efficiently on a variety of massively parallel computers and includes sophisticated techniques for assimilation of satellite altimeter sea surface height and temperature data, as well as *in situ* temperature, salinity, and float displacement. The goal of this project is to develop and implement a comprehensive data management and distribution strategy that allows easy and efficient access to HYCOM-based ocean prediction system outputs to coastal and regional modeling sites, to the wider oceanographic and scientific community including climate and ecosystem researchers, and the general public especially students in middle and high schools. This is to be accomplished through a data sharing system using existing open source software packages to distribute ocean prediction system data via the Internet. The HYCOM Data Sharing System is built upon two existing software components: the Open Project for a Network Data Access Protocol (OPeNDAP) and the Live Access Server (LAS). OPeNDAP provides uniform binary-level access to scientific data on the Internet (see <http://www.opendap.org>).

The Coupled Boundary Layers Air-Sea Transfer Defense Research Initiative focuses on processes that occur in the oceanic and atmospheric wave boundary layers (i.e., regions influenced by ocean surface waves). This Office of Naval Research program combines observational and modeling components in all of its investigations. These investigations will focus on processes that couple the turbulent atmospheric and oceanic boundary layers across the interface through the exchange of momentum, mass, and heat. The observational components include *in situ* investigations of ocean-atmospheric turbulence and mean flow from fixed towers and moorings, remote sensing of 2- and 3-D structure of the boundary layers and ocean surface, appropriate surface wave measurements with particular emphasis on small-scale and breaking waves, and Autonomous Underwater Vehicle and aircraft-based measurements.

The Monterey Bay 06 (MB 06) experiment will build on earlier work of the Autonomous Ocean Sampling Network I and II programs to demonstrate the capability to coordinate a diverse collection of manned and unmanned observing platforms within the context of data-assimilation models to form an effective ocean observing and undersea monitoring system. MB 06 is an integrated experiment that involves the interaction and coordination of four related but distinct programs: Adaptive Sampling and Prediction (ASAP), Undersea Persistent Surveillance (UPS, or UPS/PLUSNet), Assessing the Effects of Sub-Mesoscale Ocean Parameterizations (AESOP), and Layered Organization in the Coastal Ocean (LOCO).

Polar Regions Research

A priority in the CCSP research plan has been the polar and sub-polar regions, which have exhibited more rapid changes than the lower latitudes. The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) is America's lead Federal laboratory for polar and sub-polar research. The CRREL research program responds to the needs of the military, but much of the research also benefits the civilian sector and is funded by non-military customers such as NSF, NOAA, NASA, DOE, and State governments. DOD research has examined impacts of climate change on retreating Arctic sea ice—defining the requirements for U.S. Coast Guard icebreaking ships for the next 30 years. Satellite data show that the extent of Arctic sea ice has decreased by about 10%, and the sonar data collected by U.S. Navy submarines in the Arctic between 1957 and 2000 show the average ice thickness has decreased between 33 and 42%. CRREL and the University of Alaska are developing a web-accessible Alaska Engineering Design Information System—an analytic toolkit for engineers that presents a broad array of geospatial terrestrial, oceanic, and atmospheric environmental data in a Geographic Information System.

Related Research

Other DOD-sponsored research and supporting infrastructure, not described above, also contribute to observing, understanding, and predicting environmental processes related to global change. Associated research programs include theoretical studies and observations of solar phenomena, monitoring and modeling of unique features in the middle and upper atmosphere, terrestrial and marine environmental quality research, and energy conservation measures. DOD's continued investment in environmental infrastructure—such as the Oceanographic Research Vessel Fleet, and the various services' operational oceanographic and meteorological computational centers—will continue to provide data and services useful to CCSP.

DEPARTMENT OF ENERGY

Principal Areas of Focus

Research supported by DOE's Office of Science is focused on the effects of energy production and use on the global climate system, primarily through studies of climate response to changes in greenhouse gas and aerosol concentrations. Research covers three program areas: 1) climate change modeling, 2) climate forcing, and 3) climate change response.

Program Highlights for FY 2007

DOE will continue support of climate change research at its National Laboratories and other public and private research institutions, including universities. In support of CCSP, the DOE Office of Science's Climate Change Research Program will continue to provide the data and predictive understanding that will enable objective, scientifically rigorous assessments of the potential for, and consequences of, human-induced climate change

Climate Change Modeling

DOE continues to develop, improve, evaluate, and apply fully coupled atmosphere-ocean-sea ice-land surface general circulation models (GCMs) that simulate climatic variability and change over decadal to centennial time scales. As one of its contributions to the suite of synthesis and assessment products (SAPs) being prepared by CCSP, DOE will lead the effort on SAP 3.1, "Climate Models: An Assessment of Strengths and Limitations for User Applications."

In FY 2007, DOE researchers will participate in the analysis of multi-model ensemble runs under various forcing scenarios as part of the U.S. contribution to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, scheduled for release in 2007. IPCC model simulations from major national and international high-end modeling centers are currently archived at Lawrence Livermore National Laboratory (LLNL)/Program for Climate Model Diagnosis and Intercomparison (PCMDI), and made accessible to the climate research community. Under the DOE-wide Scientific Discovery through Advanced Computing (SciDAC) initiative, DOE will support model development of the CCSM to incorporate atmospheric chemistry and coupled biogeochemistry, in addition to improved physics and dynamics. DOE will also continue ongoing development of high-resolution comprehensive coupled GCMs that incorporate more accurate and verified representations of clouds and other important climatic processes. DOE will continue support of innovative approaches to climate model development—for example, the geodesic grid model intended to lead to a prototype climate model that could potentially overcome some of the problems and limitations of current generation climate models.

Climate Forcing

Collection and analysis of data from DOE's Atmospheric Radiation Measurement (ARM) Cloud and Radiation Test Bed (CART) sites will continue in FY 2007 to improve understanding of the radiative transfer processes in the atmosphere and to formulate better parameterizations of these processes, especially cloud and aerosol effects for use in climate models. DOE will also report on results of two major international campaigns: Tropical Warm Pool – International Cloud Experiment (TWP-ICE) and the 1-year deployment of the ARM Mobile Facility in Niger, Africa. The latter is part of the field phase of the African Monsoon Multidisciplinary Analysis (AMMA) to obtain atmospheric and radiation data on meteorological conditions ranging from deep, tropical convective clouds in the humid tropical air masses prevalent in the wet season to the aerosol-laden dry air masses found during the dry season. AMMA field data will provide unique opportunities to evaluate and improve the parameterization schemes used in climate models across a wide range of meteorological conditions. The TWP-ICE was conducted around the ARM site in Darwin, Australia, and focused on the effects of cirrus clouds on the transfer of radiation in the atmosphere. TWP-ICE employed multiple research aircraft and balloon-borne meteorological sensors from an array of sites to measure cloud properties and their impacts on the transfer of radiation in the atmosphere throughout the storm life cycle as well as the atmospheric state. Data from this experiment will be used to both evaluate and test how well existing models simulate cloud properties and to improve the modeling of cloud properties and their effects on the transfer of radiation in the atmosphere. In 2007, the mobile facility will be deployed to the Black Forest in Germany to participate in the Initiation of Convection and the Microphysical Properties of Clouds in Orographic Terrain (AMF + COPS). The region of deployment can be characterized by significant orographic precipitation with most of the summertime precipitation being convective. The experiment is designed to improve the prediction of precipitation in this environment. In 2007, ARM will conduct an experiment to study the impact of land surface conditions on continental cumulus convection. This experiment—the Cloud LAnd Surface Interaction Campaign (CLASIC)—will last 1-3 months and will straddle the winter wheat harvest when large changes in the land surface lead to large changes in the surface albedo, latent heat flux, and sensible heat flux. By DOE's invitation, CLASIC will be developed further as an integrated, interagency project—contingent on FY 2007 funding and on expressions of multi-agency interest.

DOE's Atmospheric Science Program will continue research in FY 2007 to reduce uncertainties in aerosol radiative forcing of climate. Research will focus specifically on atmospheric loading and geographical distribution of aerosols, on the properties that influence their scattering and absorption of radiation, their influence on the microphysical properties of clouds, and the processes that influence aerosol loading, geographical distribution, and properties. In FY 2007 a campaign will be conducted, in conjunction with the ARM Program, to examine interactions of aerosols with fair-weather cumulus clouds. Analysis of data from prior field studies will continue, principally from a FY 2005 campaign that examined aerosol influences on marine stratus and a FY 2006 campaign conducted in and around Mexico City to examine the properties and processes of aerosols emanating from a large metropolitan area. Data from the campaign will be used to characterize changes in aerosol composition, size distribution, light scattering coefficient, absorption coefficient, optical depth, soot-specific absorption, and radiative fluxes at the surface. Results will be utilized to develop or improve detailed models of aerosol processes required by the climate modeling community.

DOE's carbon cycle research will continue to improve understanding of the role and importance of terrestrial ecosystems in the global carbon cycle. Research in FY 2007 will address the questions and elements described in Chapter 7 of the *CCSP Strategic Plan*. DOE's Terrestrial Carbon Processes (TCP) research will continue to contribute to the North American Carbon Program (NACP) through support of experiments, observations, and modeling of atmospheric CO_2 and the terrestrial carbon cycle. In FY 2006, TCP was formally reviewed, and it was recommended that the program continue to focus on the AmeriFlux network of observations, and that experimental, modeling, and synthesis research continue to provide fundamental information for understanding the terrestrial carbon cycle, including exchange of CO_2 between terrestrial systems and the atmosphere. Temporal and spatial observations of gross and net carbon dioxide fluxes, and real-time information on ecosystem carbon states and sinks, will be made available to researchers that are investigating regional CO_2 exchange, continental-scale carbon sinks and sources, and carbon cycle-climate relationships. DOE will also support the NACP strategy of a model-based comparison of "bottom-up" (distributed ecosystem models driven by land surface and meteorological information) and "top-down" (inferring spatially distributed surface fluxes from atmospheric measurements) approaches to estimating ecosystem carbon dioxide fluxes for different regions of the United States. DOE will provide information on biogeochemical, physiological responses and terrestrial ecosystem feedbacks related to climate change as part of joint carbon cycle-climate change research to improve simulation models.

Climate Change Response

DOE will continue to design, implement, and maintain large-scale and long-term experimental field manipulations of environmental factors affected by energy production in important North American ecosystems. This includes support of the Free-Air CO_2 Enrichment (FACE) experimental facilities for study of the response of terrestrial ecosystems to elevated atmospheric concentrations of carbon dioxide (and in some cases ozone). The goal is to understand, and be able to predict, effects of environmental change and variability on the structure and functioning of terrestrial ecosystems. The research focuses on the physiology, growth, and reproduction of plants and microbes; nutrient and water cycling in ecosystems; plant community dynamics; plant-microbe interactions; and acclimation and adaptation of plants, microbes, and whole ecosystems to environmental change and variability.

Ongoing experimental research will be continued in FY 2007, including field manipulations of temperature, precipitation and soil moisture, carbon dioxide concentration, ozone concentration, and/or enhanced atmospheric nitrogen deposition in a range of terrestrial ecosystems, including boreal forest, arid shrublands and desert, temperate grasslands, temperate woodlands, and temperate deciduous and evergreen forests. Such experiments will provide the data and information needed to evaluate (test) the ability of ecological models to realistically predict effects of environmental change and variability on terrestrial ecosystems; such models form the basis of most assessments of potential effects of environmental change on ecosystems. The research initiative implemented in FY 2004 dealing with "scaling" in ecological systems will also be continued in FY 2007. This initiative will continue to examine how quantitative information obtained at the level of macromolecules (e.g., genes and enzymes) can be used to understand and predict how processes and states of whole terrestrial ecosystems would be affected both directly and indirectly by natural and human-induced environmental changes, such as climatic changes caused by energy production. Ecosystems that will be studied include forest, shrubland, grassland, and crop.

The DOE Integrated Assessment of Global Climate Change Research Program will continue to support research that examines and models global economies, technologies that emit greenhouse gases, and natural systems associated with climate change. These studies help provide understanding of the relative efficiencies and impacts of potential mitigation strategies. In FY 2007, the two large integrated assessment models funded by the program will improve their representation of renewable energy derived from biological sources. The portrayal of uncertainty in emission scenarios will also be studied to help identify methods that represent important variability with a small number of alternative scenarios. In FY 2007, research will develop a new modeling tool to assess the effects of technological change in agriculture and forestry on the future path of global carbon sequestration. The research will assess the influence of technology on land uses, explicitly assessing carbon flows to develop estimates of future carbon emission or sequestration. In FY 2007, research will generate empirical information on the direct costs and benefits of research and development (R&D) on low-emission technologies as well as the "external" benefits ("spillover effects") from R&D. The key question is whether an increase in climate R&D represents new R&D spending, or whether some (or all) of the additional climate R&D comes at the expense of other R&D.

DOE will also continue support of its Global Change Education program in FY 2007, including support of undergraduate and graduate students through the DOE Summer Undergraduate Research Experience (SURE) and the DOE Graduate Research Environmental Fellowships (GREFs). Support will also be continued for the Carbon Dioxide Information and Analysis Center (CDIAC) to enable it to respond to data and information requests from users all over the world who have a need for data on, for example, greenhouse gas emissions and concentrations.

Related Research

DOE plays a major role in carbon sequestration research to reduce atmospheric concentrations of energy-related greenhouse gases, especially carbon dioxide, and their net emissions to the atmosphere. The research builds on, but is not part of, the CCSP. It focuses on both developing the scientific information needed to enhance the natural sequestration of excess atmospheric carbon dioxide in terrestrial systems, and assessing the potential environmental consequences and ancillary benefits of that enhanced sequestration. It also includes research to develop biotechnological approaches for sequestering carbon either before or after it is emitted to the atmosphere. Funding for DOE's carbon sequestration research is part of the Climate Change Technology Program (CCTP). CCTP also provides related research funding to support a balanced and diversified portfolio of advanced technology R&D, focusing on energy-efficiency enhancements; low-GHG-emission energy supply technologies; carbon capture, storage, and sequestration; and technologies to reduce emissions of non-CO_2 gases. Together, CCSP and CCTP will help lay the foundation for future progress. Advances in the climate change sciences under CCSP can be expected to improve understanding about climate change and its impacts. Similarly, advances in climate change technology mitigation under CCTP can be expected to bring forth an expanded array of advanced technology options at a lower cost that will reduce greenhouse gas emissions.

DEPARTMENT OF HEALTH AND HUMAN SERVICES

National Cancer Institute (NCI)
National Eye Institute (NEI)
National Institute of Arthritis and Musculoskeletal and Skin Diseases (NIAMS)
National Institute of Environmental Health Sciences (NIEHS)

Principal Areas of Focus

The Department of Health and Human Services supports a broad portfolio of research related to environmental health and the health effects of global change. Included in the U.S. Climate Change Science Program is research supported by the National Institutes of Health (NIH) that focuses on exposure to ultraviolet (UV) and near-UV radiation. The principal objectives of the four NIH institutes supporting this research include an increased understanding of the effects of UV and near-UV radiation exposure on target organs (e.g., eyes, skin, immune system), the molecular changes and genetic susceptibilities that lead to these effects, and the development of strategies to prevent the initiation or promotion of disease before it is clinically defined.

In addition to UV and near-UV radiation research, HHS also supports other research related to the health effects of global change. For example, the National Institute of Environmental Health Sciences (NIEHS) supports research on the health effects of 1) air pollution and temperature, 2) agricultural chemicals, and 3) materials used in new technologies to mitigate or adapt to climate change. In addition, the Centers for Disease Control and Prevention (CDC) is engaged in a number of activities related to climate change, such as emerging and reemerging infectious diseases. Such related research is growing in importance.

Program Highlights for FY 2007

The NIEHS program supports grants and intramural projects that investigate the effects of UV exposure on the immune system, aging process, sensitive tissues such as the retina and skin, and methods to reduce these harmful effects. Examples of research include projects that will characterize the DNA-damaging and mutagenic properties of UV-A radiation, a component of the solar spectrum that has been linked to melanoma, then attempt to find a molecular link between exposure to sunlight and melanoma.

The National Toxicology Program (NTP) funded and operated by NIEHS is carrying out a systematic analysis of commercially available sunscreens to characterize several nanoscale metal oxides (e.g., titanium, zinc) currently used with regard to their dermal penetration and photocatalytic action. Careful attention is being paid to determining critical aspects of size, surface area and chemistry, crystallinity, and biopersistence in relation to both dermal penetration and potential for toxicity in the presence or absence of simulated solar light.

The National Eye Institute (NEI) supports studies on the impacts of UV radiation on the eye (retinal damage as well as corneal capacity). A major initiative is underway to determine how and why eye cataract develops and to search for ways to prevent or slow the progression of cataract, an age-related eye disease that affects 17-20 million people globally. This project is investigating the role of UV-B radiation, which has been implicated as a specific risk factor in cataract development. Another important area of research is the understanding of certain detoxification systems in the eye and how they combat damage from UV-B radiation. The goal of this effort is to identify drugs that might have therapeutic or preventative applications. One study is investigating how corneal epithelial cells prevent damage to their DNA by reactive oxygen species generated by UV light and whether the protection against damage provided by nuclear ferritin in corneal epithelial cells can be extended to other cell types in which reactive oxygen species may have deleterious effects.

The National Cancer Institute (NCI) is supporting a wide range of studies to characterize the etiology, biology, immunology, and pathology of a variety of changes in the skin (morphological effects that might precede skin cancer), including photoaging, non-melanoma skin cancers, and melanoma caused by exposure to UV radiation. In addition, NCI is supporting studies to reduce the risk of melanoma and non-melanoma skin cancer through the development of clinically useful primary and secondary prevention strategies. One study is developing, implementing, and evaluating solar protection programs for middle school children. The interventions target school, community, recreation and beach settings, primary care practices, and parents. The interventions are based on theories that include social influence, psychological factors, and cognitive decisional factors in adolescence. Other studies are looking at the role of UV light exposure in the development of second malignant neoplasms in cancer survivors.

The National Institute of Arthritis, Musculoskeletal, and Skin Diseases (NIAMS) supports basic and clinical research on the effects of UV-A and UV-B radiation on skin. Examples of current studies include research to better understand how vitamin D3 is made and processed in the skin. These chemical reactions require ultraviolet radiation. Another study looks at the effects of UV-B radiation on the stability of cell cycle regulatory proteins and will yield insight into the mechanisms by which UV-B radiation increases the risk of non-melanoma skin cancer. A third study examines the ability of green tea polyphenols to protect against UV-B-induced skin cancers through the augmentation of the repair of UV-damaged DNA. Previous studies in this area of research have included studies on the role of overexposure to UV light in the development and exacerbation of vitiligo, a pigmentary disorder that leaves patients with disfiguring white skin patches that increase in size over time. Another patient-oriented research project studied the molecular mechanisms for the exaggerated response to UV-B of a polymorphism that is strongly associated with a photosensitive form of lupus erythematosus. Another study worked on the effect of UV-R on Langerhans cells, star-shaped cells in the germinative layer of the epidermis, and on immunity in skin. Using gene array technology, scientists identified 52 genes that are consistently up-regulated by UV-R.

Related Research

Renewed concern about emerging and reemerging infectious diseases has prompted increased attention to a variety of insect and tick-borne diseases whose incidence would be affected by environmental change. One area of research, conducted by CDC, is the use of remote sensing to study ecologic systems relevant to transmission of specific infectious diseases, especially vector-borne diseases. Examples of research by CDC using remote-sensing and other geographic/spatial technologies include studies of hantavirus, plague, and Chagas disease. Sin Nombre virus, carried by the deer mouse, causes hantavirus pulmonary syndrome (HPS) in the Americas. Since 1994, CDC has collaborated with local academic institutions to study the effect of climatic variation, such as that associated with El Niño Southern Oscillation (ENSO), on changes in population densities of deer mice. The goal of the U.S.-based studies is to develop a model using satellite imagery to predict increases in risk of HPS at specific locations across the western United States. These studies have already helped CDC predict and post warnings of increased disease risk in the southwestern United States.

A CDC-sponsored study of plague in the four corners area of the U.S. Southwest also employs remote-sensing technology to develop a predictive model for increased plague transmission in the area. Finally, CDC is applying GIS and ecological niche analysis using GARP (Genetic Algorithm for Rule Set Prediction), a form of spatial/temporal analysis, to study the eco-epidemiology of Chagas disease in Guatemala, Mexico, Brazil, and Argentina, and to improve collaborative efforts aimed at disease surveillance and control in these regions.

CDC also sponsors broader research related to climate change and infectious diseases. CDC's Division of Vector-Borne Infectious Diseases is currently collaborating on studies of how the transmission of vector-borne diseases may be affected by the environment. Its Guatemala field station is studying the impact that adverse climatological events, such as El Niño and Hurricane Gilbert, have had on the transmission dynamics of malaria and other diseases. These catastrophic events create tremendous changes that can simultaneously create new vector habit, reduce the levels of sanitation, and overwhelm the ability of the public health system to respond. Other CDC units are collaborating on studies of the effects of climate change on dengue on the U.S.-Mexico Border.

DEPARTMENT OF THE INTERIOR / U.S. GEOLOGICAL SURVEY

Principal Areas of Focus

DOI/USGS research contributes directly to CCSP strategic goals, principally through studies designed to understand the interactions between climate, earth surface processes, and ecosystems on time scales ranging from years to millennia. By combining the expertise of hydrologists, geologists, biologists, geographers, and remote-sensing scientists within one organization, USGS supports truly interdisciplinary research in the following major focus areas:

- Studies of climate history and impacts on landscapes and ecosystems
- Hydrologic impacts of climate change
- Carbon cycle science
- Land-use and land-cover changes
- Decision-support research and development.

The goal of global change research at USGS is to improve knowledge and understanding of the Earth's past and present climate and environment, the forces bringing about changes in the Earth's climate, and the sensitivity and adaptability of natural and managed ecosystems to climate changes.

Program Highlights for FY 2007

Earth Surface Dynamics

The Earth Surface Dynamics program has the following research objectives:

- Document the nature of climatic and environmental change and variability on time scales ranging from years to millennia.
- Develop fundamental understanding of interactions between climate, earth surface processes, and marine and terrestrial ecosystems on time scales ranging from years to millennia.
- Seek to understand impacts of climate change and variability on landscapes and marine and terrestrial systems.
- Model and anticipate the effects of climate change and variability on natural and human systems.
- Provide information on the relative sensitivity, adaptability, and vulnerability of ecosystems, resources, and regions to climatic change and variability to support land and resource management and policy decisions.

Geographic Analysis and Monitoring

Research is directed to the understanding of the rates, causes, and consequences of landscape change over time. This knowledge is used to model processes of landscape change and to forecast future conditions. Studies are designed to document and understand the nature and causes of changes occurring on the land surface; to assess the impacts of land surface changes (including urbanization) on ecosystems, climate variability, biogeochemical cycles, hydrology, and human health; and to develop the best methods to incorporate science findings in the decisionmaking process.

Hydroclimatology

Research on effects of climate change and variability on the hydrologic cycle focuses on characterizing, and developing predictive methods related to, the hydroclimatology of North America. This includes identification of seasonal variations in regional streamflow in relation to atmospheric circulation (for regional streamflow prediction and flood/drought hazard assessment); the linkage between atmospheric circulation and snowpack accumulation (for forecasting spring and summer water supply in the western United States and for flood forecasting), as well as glacier mass balance; and the physical and chemical variability in riverine and estuarine environments in relation to large-scale atmospheric and oceanic conditions (to discriminate natural from human-induced effects on such systems). It also includes documenting the long-term behavior of hydrologic systems in response to past climatic variations and changes (from decades to hundreds of thousands of years) as well as more recent (decadal) hydrologic trends. The program maintains an active effort to develop improved representations of terrestrial hydrologic processes in general circulation and regional climate models. In broad terms, these activities are aimed at improving statistical and deterministic methods for predicting hydrologic hazards and related environmental conditions on monthly to interannual time scales.

Carbon Cycle

USGS conducts a broad range of carbon cycle research focused on North America, which includes:

- *Assessment of Carbon Stocks and Soil Attributes*—Determining the spatial distribution of carbon in the terrestrial environment in relation to historical natural and human processes, as a basis for initializing dynamic models of soil carbon. Measuring soil chemistry has focused on the Mississippi and Delaware River basins, the latter in collaboration with the USDA Forest Service Forest Inventory and Analysis Program.
- *Carbon Sequestration in Sediments*—Studying the re-deposition of eroded soils and sediments (and their associated organic carbon) which sequesters large quantities of carbon, buried at the base of slopes and in wetlands, riparian areas, and reservoirs.
- *Carbon Sequestration in Wetlands*—Field and laboratory process studies, spatial analysis, and modeling are being used in wetlands of the Lower Mississippi River Valley and the Prairie Pothole Region to quantify the influence of land-use change on carbon sequestration and greenhouse gas emissions and to identify environmental factors controlling carbon sequestration. These studies will provide recommendations and decision-support tools to resource managers to maximize carbon sequestration benefits consistent with DOI goals for restoration of ecosystem services such as habitat, flood storage, and water quality.
- *Landscape Dynamics and Vegetation Change*—Examining the long-term dynamics of vegetation change in relation to climate change and variability. A detailed history of vegetation change in the western United States is being constructed. Past changes are used to model vegetation response to climatic variables. This knowledge is applied in forecasting the effects of future climate change on the distribution of vegetation in the western United States.
- *Fate of Carbon in Alaskan Landscapes*—Expanding process studies and modeling to better understand both the historic and modern interactions among climate, surface temperature and moisture, fire, and terrestrial carbon sequestration. Cold region forests (boreal ecosystems) contain large carbon reserves that are highly susceptible to changes in climate.
- *Exchanges of Greenhouse Gases, Water Vapor, and Heat at the Earth's Surface*—Employs field measurements, remote sensing, and modeling of carbon fluxes to develop estimates of gross primary productivity, respiration, and net ecosystem exchange at flux tower sites, and uses remotely sensed data to extrapolate these carbon fluxes to ecoregions.

Changes in Ecosystems

USGS global change research on ecosystems aims to determine the sensitivity and response of ecosystems and ecological processes to environmental factors, including existing climate and natural and anthropogenic impacts, at the local, landscape, regional, and continental level; to assess and predict how future environmental conditions may affect the structure, function, and long-term viability of natural and human-impacted ecosystems; and to provide scientific knowledge and technologies needed for conservation, rehabilitation, and management of sustainable ecosystems. Current USGS ecosystems research focuses on:

- The relative sensitivity of biological resources and geographic areas of the Nation to global changes in order to detect early changes and prioritize action
- The causal mechanisms underlying ecosystem responses to global change
- The role of scaling in understanding and managing the spatial and temporal responses of biological systems to global change
- Development and testing of management options for adapting to the effects of global change and minimizing undesired effects of global change.

Satellite Data Management and Dissemination

USGS operates and continually enhances the capabilities of the Center for Earth Resources Observation System (EROS) to serve as the National Satellite Land Remote-Sensing Data Archive, by maintaining existing data sets, adding new ones, and converting older data sets from deteriorating media to modern, stable media. The archive's holdings are used for environmental research, land management, natural hazard analysis, and natural resource management and development with applications that extend well beyond U.S. borders. The worldwide community of archive users includes personnel in Federal, State, local, and tribal governments, researchers at academic institutions, private enterprise, and the public.

Land Use and Land Cover

The Land Cover Characterization Program was started in 1995, to address national and international requirements for land-cover data that were becoming increasingly sophisticated and diverse. The goal is to be a national and international center for excellence in land-cover characterization, via:

- Development of state-of-the-art multiscale land-cover characteristics databases used by scientists, resource managers, planners, and educators (global and national land cover)
- Contribution to the understanding of the patterns, characteristics, and dynamics of land cover across the Nation and the Earth (urban dynamics and land-cover trends)
- Pursuit of research that improves the utility and efficiency of large-area land-cover characterization and land-cover characteristics databases
- Serving as a central facility (Land Cover Applications Center) for access to, or information about, land-cover data.

Related Research

DOI also sponsors contributing research programs addressing the collection, maintenance, analysis, and interpretation of short- and long-term land, water, biological, and other geological and biological processes and resources through dispersed observing networks; research in land use and land cover, including creation of maps and digital data products; and inventorying and monitoring of biological habitats, resources, and diversity.

DEPARTMENT OF STATE

Principal Areas of Focus

Through Department of State annual funding, the United States is the world's leading financial contributor to the United Nations Framework Convention on Climate Change (UNFCCC) and to the Intergovernmental Panel on Climate Change (IPCC)—the principal international organization for the assessment of scientific, technical, and socioeconomic information relevant to the understanding of climate change, its potential impacts, and options for adaptation and mitigation. Recent DOS contributions to these organizations provide substantial support for global climate observation and assessment activities in developing countries. DOS also works with other agencies in promoting international cooperation in a range of bilateral and multilateral climate change initiatives, including: the Asia-Pacific Partnership on Clean Development and Climate, the Carbon Sequestration Leadership Forum, the Group on Earth Observations, the Methane-to-Markets Partnership, the International Partnership for a Hydrogen Economy, and the Generation IV International Forum.

Program Highlights for FY 2007

During FY 2007, DOS will continue to support the activities of the UNFCCC and the IPCC, including finalization of the IPCC *Fourth Assessment Report*, and will advance the bilateral and multilateral partnerships for global climate science, technology, and observation that were undertaken in the FY 2005-2006 time frame.

DEPARTMENT OF TRANSPORTATION

Principal Areas of Focus

The Department of Transportation conducts research and uses existing science to improve decisionmaking tools to address climate change. USDOT supports research that 1) examines the potential impacts of climate variability and change on transportation infrastructure and services; 2) increases energy efficiency and reduces greenhouse gases; and 3) improves transportation greenhouse gas data and modeling. USDOT has many programs that have either direct or indirect climate benefits and is working to develop cross-modal strategies to reduce greenhouse gas emissions.

USDOT's Climate Change Center is the Department's focal point for information and technical expertise on climate change. The Center coordinates research, policies, and actions related to transportation and climate change with USDOT's component organizations. Supporting USDOT's core goals of safety, mobility, environmental stewardship, and security, the Center promotes comprehensive approaches to reduce greenhouse gases, to prepare for the potential impacts of climate change, and to develop necessary adaptations to transportation operations and infrastructure. The Center's three primary objectives are to:

- Promote cost-effective strategies that reduce greenhouse gas emissions while supporting improved transportation safety, mobility, and efficiency
- Foster strategies to avoid, mitigate, or adapt to the potential impacts of climate change on the transportation system
- Provide leadership to the transportation community and coordinate USDOT multi-modal activities on climate change.

The Center supports CCSP goals through these objectives. Specifically, the Center aims to inform CCSP Goal 4 by identifying and providing scientific inputs for evaluating adaptation options and CCSP Goal 5 by supporting adaptive management and planning for physical infrastructure sensitive to climate variability and change.

In addition to participating in the Center, the Federal Aviation Administration (FAA) has independent programs to reduce greenhouse gases and support CCSP goals. FAA conducts research to support CCSP Goal 2, leveraging research with other U.S. Government agencies to reduce uncertainties surrounding aviation emissions and their effect on climate change. FAA research through the Partnership for Air Transportation Noise and Emissions Reduction (PARTNER) Center of Excellence addresses the impact of aircraft contrails on climate change. FAA also has a number of ongoing operational initiatives to reduce the amount of greenhouse gases produced by aviation, including improved air traffic management, reduced vertical separation minimums, and the voluntary airport low emissions program that assists in deploying low emissions technology to airport operations. FAA also lends technical expertise and data to the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC).

Program Highlights for FY 2007

USDOT's Climate Change Center is undertaking several research projects that support CCSP Goals 4 and 5, and are expected to be completed in FY 2007:

- Developing a tool to allow comparative analysis of emissions from different modes of transportation, including aviation, automobile, marine, and diesel transportation
- Exploring adaptation to potential impacts of climate change by partnering with the Transportation Research Board of the National Academies
  - Reexamine the role of design standards for transportation infrastructure in light of potential impacts from climate change
  - Develop operational responses to potential climate change impacts
  - Review approaches to decisionmaking under uncertainty
- Conducting an emissions analysis of freight transport, comparing land-side and water-side short-sea routes to develop and demonstrate a decision modeling tool
- Determining the potential effects of sea level rise on national transportation infrastructure.

The Center sponsors CCSP Synthesis and Assessment Product 4.7, "Impacts of Climate Variability and Change on Transportation Systems and Infrastructure–Gulf Coast Study." This project—initiated under the President's Climate Change Research Initiative—is a joint research effort with USGS. A Federal Advisory Committee was formed in 2006, and Phase I will be completed in 2007. Phase I will provide an integrated overview of infrastructure sensitivities in the region.

The Office of the Secretary is funding several projects for FY 2007 completion, including a *Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation*. The Guidebook will be designed for use by companies and individual freight operators.

Related Research

Many of DOT's programs have ancillary climate benefits:

- The Federal Highway Administration has numerous programs to prepare the highway system for weather irregularities and reduce air pollutants:
  - *Road Weather Management Program*. This program seeks to better understand the impacts of weather on roadways. The Clarus initiative will develop and demonstrate a national integrated surface transportation road weather observing, forecasting, and data management system.
  - *It All Adds Up to Cleaner Air*. This collaborative effort advocates simple, convenient actions people can take in their daily lives to contribute to an overall improvement in air quality.
  - *Congestion Mitigation and Air Quality (CMAQ) Improvement Program*. The CMAQ program provides over $8.6 billion in funds to State transit agencies to invest in projects that reduce emissions from transportation-related sources over a period of 6 years (2004-2009).
  - *Idle-Reduction Activities*. DOT, EPA, and DOE have provided funding for the implementation of idle-reduction projects around the country (both on-board and off-board technologies) for transportation, air quality, and energy stakeholders. The projects have resulted in reductions in criteria air pollutants, such as NO_x, as well as reductions in CO_2 emissions. This initiative has expanded to include idling emissions from marine, rail, and off-road heavy-duty engines.

- The National Highway and Transit Safety Administration sets new Corporate Average Fuel Economy standards for light trucks, increasing energy efficiency and thus decreasing greenhouse gas emissions.
- FAA is developing numerous environmental analytical tools, including the System for assessing Aviation's Global Emissions (SAGE). This system generates aviation emission inventories for baseline conditions, forecasts technology and operational improvements, and uses market-based measures to reduce fuel use. It is used to calculate aviation's fuel efficiency goal and assess cost-effective options to limit or reduce greenhouse gas emissions.
- The Federal Transit Administration (FTA) Fuel Cell Program has researched and demonstrated fuel cell bus technology since the mid-1990's. FTA also conducts alternative fuels research.
- Other programs for congestion mitigation, hydrogen-powered transportation, and transit developments all will potentially reduce greenhouse gases.

AGENCY FOR INTERNATIONAL DEVELOPMENT

Principal Areas of Focus

The Famine Early Warning System Network (FEWS NET) is an innovative application of science for support of efforts at alleviating risks related to existing climate variability or the potential for climate change. Through FEWS NET, USAID is able to provide decisionmakers—both in the United States and in the developing world—with information designed to support policy and program interventions for effective and timely response to drought and food insecurity. FEWS NET historically focused its activities in 18 drought-prone countries across sub-Saharan Africa and, as of 2003, FEWS NET has expanded its coverage to include select countries in Central Asia and Latin America and the Caribbean. In addition to monitoring a wide variety of socioeconomic indicators to identify levels of food insecurity, FEWS NET monitors and analyzes remotely sensed data and ground-based meteorological, crop, and rangeland observations to track the progress of rainy seasons and crop production in semi-arid regions, in order to identify early indications of reduced food availability and access.

Program Highlights for FY 2007

In FY 2007, FEWS NET will continue to provide seasonal monitoring in relationship to analyses of food insecurity conditions in Africa and Central America, as well as in Haiti and Afghanistan. A major element of this work has been to strengthen information networks that collect and analyze data to reveal intra- and interannual climate variability trends as they relate to possible longer term climate variability and change.

ENVIRONMENTAL PROTECTION AGENCY

Principal Areas of Focus

EPA's Global Change Research Program is stakeholder-oriented, with primary emphasis on evaluating the potential consequences of global change (particularly climate variability and change) on air quality, water quality, ecosystems, and human health in the United States. This includes improving the scientific basis for evaluating effects of global change in the context of other stressors, and evaluating the risks and opportunities presented by global change. EPA uses the results of these studies to investigate adaptation options to improve society's ability to effectively respond to the risks and opportunities presented by global change. The program is multidisciplinary and emphasizes the integration of the concepts, methods, and results of the physical, biological, and social sciences into decision-support frameworks. This work is consistent with and closely coordinated with the *CCSP Strategic Plan*.

The planning and implementation of EPA's program is integrated by the CCSP with other participating Federal departments and agencies to reduce overlaps, identify and fill programmatic gaps, and add integrative value to products and deliverables produced under the CCSP's auspices. EPA coordinates with other CCSP agencies to develop and provide timely, useful, and scientifically sound information to decisionmakers. This includes support for the production of CCSP synthesis and assessment products called for in the *CCSP Strategic Plan*, and the development of decision-support tools for resource managers and decisionmakers. Also, as called for by the National Research Council in 2001, EPA supports and fosters projects that link the producers and users of knowledge in a dialogue that builds a mutual understanding of what is needed, what can credibly be said, and how it can be said in a way that maintains scientific credibility.

EPA's program also makes significant contributions to the high-level interagency bilateral climate dialogues that are led by the Department of State. EPA's program supports research on climate impacts and adaptation in China, Italy, Canada, and India. These activities focus on evaluating the potential consequences of climate change and adaptation strategies.

EPA's program has four areas of emphasis: air quality, water quality, ecosystems, and human health. The results of studies done in these areas are integrated at particular places (such as watersheds).

Air Quality

Studies are planned that will examine the potential consequences of global change on air quality in the United States. The long-term goal of this focus area is to provide the approaches, methods, and models to quantitatively evaluate the effects of global change on air quality, and to identify technology advancements and adaptive responses and quantify their effect on air quality.

Water Quality

Water quality is affected by changes in runoff following changes in precipitation and evapotranspiration and/or changes in land use. The program is investigating the possible impacts of global change (climate and land-use change) on water quality using a watershed approach. The water quality studies will contribute to and benefit from human health and ecosystems studies.

Ecosystems

EPA's mission is not only to protect human health but also to safeguard the natural environment. EPA provides environmental protection that contributes to making communities and ecosystems diverse, sustainable, and economically productive. Consistent with this goal, EPA's Global Change Research Program has planned three research activities that evaluate the effects of global change on aquatic ecosystems (which may include lakes, rivers, and streams; wetlands; and estuaries and coastal ecosystems); invasive nonindigenous species; and ecosystem services. EPA's investigations of the effects of global change on aquatic ecosystems will use as input the research being done by other CCSP agencies on marine and terrestrial ecosystems. Therefore, EPA's ability to successfully complete its assessments depends crucially upon the ability of other CCSP agencies to complete their related research activities.

Human Health

Since health is affected by a variety of social, economic, political, environmental, and technological factors, investigating the health impacts of global change is a complex challenge. As a result, health studies in EPA's Global Change Research Program go beyond basic epidemiological research to develop integrated health evaluation frameworks that consider the effects of multiple stresses, their interactions, and human adaptive responses. Along with health sector studies conducted in conjunction with other CCSP agencies, there are research activities focused on the possible consequences of global change on weather-related morbidity and vector- and water-borne diseases. In addition, the results from EPA's Global Change Research Program air quality studies will be used to evaluate health consequences.

Intramural and extramural research contribute to all of EPA's investigations. In an attempt to capitalize on expertise in the academic community, a significant portion of the program's resources is dedicated to extramural research grants administered through the STAR (Science to Achieve Results) program. The STAR program focuses on science to support investigations of the consequences of global change for air quality, ecosystems, and human health in the United States. EPA will continue to coordinate closely with other CCSP agencies to identify the specific topics that should be emphasized within the STAR program.

Program Highlights for FY 2007

EPA will continue to make significant contributions to the ongoing research activities of the CCSP. EPA-sponsored investigations will continue to be conducted through public-private partnerships that actively engage researchers from the academic community, decisionmakers, resource managers, and other affected stakeholders. Highlights of specific activities that will be undertaken by EPA in FY 2007 follow:

- Support the CCSP commitment to generate 21 synthesis and assessment products by leading three analyses and supporting eight others
- Produce an interim quantitative assessment of the direct effects of climate change on air quality in the United States
- Co-sponsor with NOAA a study by the National Research Council of strategies and methods for climate-related decision support
- Release a Climate Assessment Tool as part of the newer version of EPA's BASINS modeling system used by regional, State, and local agencies to perform watershed and water quality-based studies
- Study the management implications of global change and interacting stressors on the establishment and expansion of invasive species for key aquatic ecosystems

- Support the high-level interagency bilateral climate dialogues with China, Italy, Canada, and India that are being led by the Department of State
- Study current land conservation practices and provide a tool for projecting future distributions of land protection as an adaptation mechanism to climate change that restores or maintains ecosystem services
- Investigate the effects of changes in climate and land use on non-point source pollution in estuaries.

Related Research

In addition to focused CCSP activities, EPA conducts research that contributes to the characterization and understanding of risks to ecosystems and to human health. The ecosystems-based research is designed to understand and predict ecosystem exposure, responses, and vulnerabilities to high-risk chemicals and non-chemical stressors (e.g., invasive species, genetically altered organisms) at multiple scales of biological organization and geographic scales. The research in human health is oriented toward assessing the cumulative health risks to humans (e.g., cancer, reproductive, cardiovascular)—including high-risk subpopulations (e.g., children)—from chemical stressors emanating from multiple sources. Both of these major research areas will be affected by and are inextricably interrelated with climate change.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Principal Areas of Focus

The National Aeronautics and Space Administration provides worldwide science and technology leadership to understand the integrated global Earth system through pioneering advancements of Earth system observations, research, and modeling enabled by satellites. NASA's programs encompass virtually every element and component in the *Strategic Plan for the U.S. Climate Change Science Program*. NASA has the largest agency investment in the 13-agency Climate Change Science Program (CCSP), and the Science Mission Directorate Earth Science Division (ESD) is the NASA leader for CCSP.

ESD encompasses the global atmosphere from the surface of the land and sea to the top of the stratosphere; the global oceans including sea ice; all land surfaces including snow and ice; the solid Earth beneath the ocean and land; the ecosystems in the air, oceans, and land; and all the interactions between the atmosphere, oceans, land, snow, ice, and associated ecology, including humans. The multitude of integrated global Earth system processes and their interactions have important time scales from hours to centuries that include weather over short- and long-term climate time periods, and have horizontal distances from kilometers (regional) to the entire globe. NASA's Heliophysics Division contributes to integrated global Earth system science through studies of the Sun and the interaction of its radiation with the Earth's upper atmosphere. ESD is rapidly advancing the knowledge for reliable determination of the predictability of many interrelated natural phenomena, including the societal impacts and feedback on natural and anthropogenic phenomena. ESD accelerates the realization of societal benefits from knowledge of how, when, where, and why different regions of the globe experience non-uniform environmental variability, which is important for economic growth, environmental sustainability, national security, and homeland security. ESD continues the NASA tradition of creating breakthrough scientific and technological advancements on enormously challenging issues such as global climate change.

ESD programs are also embodied in several Presidential interagency initiatives that complement the climate initiative, including the "U.S. Ocean Action Plan" (17 December 2004) and the "Strategic Plan for the U.S. Integrated Earth Observation System" (6 April 2005). ESD applies knowledge of global Earth system science obtained through space-based observations and research to improve quality of life through enhanced capabilities for prediction and mitigation of the effects of environmental hazards.

ESD pioneered the interdisciplinary field of integrated global Earth system science, which explores the global interactions among land, oceans, atmosphere, ice, and life. To study these interactions, ESD developed and deployed the constellation of Earth Observing System (EOS) satellites named Aqua, Aura, Terra, GRACE, Jason, QuikScat, TRMM, and others, along with aircraft- and surface-based sensors for extensive calibration and validation required for the development of climate-quality satellite measurements. ESD created the world's largest data and information system for collecting, processing, archiving, and distributing EOS data.

ESD focuses on integrated global Earth system science through observation, research, and modeling enabled by satellites, and technology development to address the overarching question "How is the

Earth changing, and what are the consequences for life on Earth?" Five subordinate questions describe ESD's integrated global Earth system science approach:

- How is the global Earth system changing?
- What are the primary causes of change in the Earth system?
- How does the Earth system respond to natural and human-induced change?
- What are the consequences of change in the Earth system for human civilization?
- How well can we predict future changes in the Earth system?

To accomplish integrated global Earth system science, ESD organized focus areas—some of which are shown in the accompanying table, aligned with the CCSP elements. Other focus areas are Weather and the Earth Surface and Interior, as well as a cross-cutting theme of Earth system science education and literacy.

CCSP RESEARCH ELEMENTS	NASA EARTH SYSTEM SCIENCE FOCUS AREAS
Atmospheric Composition	Atmospheric Composition
Climate Variability and Change	Climate Variability and Change
Global Water Cycle	Global Water and Energy Cycle
Land-Use/Land-Cover Change Global Carbon Cycle Ecosystems	Carbon Cycle and Ecosystems
Human Contributions and Responses	Applied Sciences

Program Highlights for FY 2007

ESD will make significant progress in contributing to increased scientific knowledge in six high-priority CCSP research areas: aerosols and clouds, carbon cycle, glacier motions, global climate-quality observations, numerical model simulations of integrated global Earth system variability, and decision-support resources development for adaptive management and planning. ESD will determine the three-dimensional structure of clouds and aerosols with satellite data recently acquired from CloudSat (a joint project with Canada) and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations, a joint project with France), which were launched on a single rocket on 28 April 2006. CALIPSO and CloudSat orbits are virtually the same as the orbits of Aura and Aqua and the French spacecraft PARASOL (Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled Observations from a Lidar). Only 8 minutes (or a distance of approximately 3,100 km on the Earth) separate the first and last satellites. This unique constellation of five satellites—known as the Afternoon- or A-Train—represents a technological breakthrough and provides for the first time near-simultaneous co-located measurements of atmospheric gases, aerosols, clouds, temperature, relative humidity, and radiative fluxes. Analyses of A-Train data will reduce the large uncertainty of the roles of clouds and aerosols in global climate change.

ESD will continue to have a leading role in understanding the global carbon cycle through the North American Carbon Program and the Ocean Carbon and Climate Change Program. ESD will contribute substantial investments in satellite and *in situ* observations and in developing ecosystem and biogeochemical models to reduce scientific uncertainties of carbon sources, sinks, and fluxes within North America and the surrounding oceans, which has recently been a subject of intense scientific interest for both scientists and decisionmakers. ESD will continue developing the Orbiting Carbon Observatory (OCO) satellite to measure for the first time global atmospheric carbon dioxide on regional scales with unprecedented accuracy to determine sources and sinks. OCO is scheduled for launch in 2008, when it will join the A-Train.

The Ice, Cloud, and land Elevation Satellite (ICESat) is measuring for the first time ice-sheet mass balance in Greenland and Antarctica, an important quantity in understanding global sea-level rise, which TOPEX and Jason data indicate was about 2 mm yr^{-1} over the past 15 years. ESD investigators will develop the first-ever vertical profiles of glacier motion from the surface to depths of hundreds of meters using simultaneous satellite synthetic aperture radar measurements recorded at X, C, and L frequencies, respectively, by partner agencies in Germany, Canada, and Japan. This is a key project of the International Polar Year 2007-2008.

To accomplish the very stringent characteristics of global climate-quality data recorded from satellites, ESD state-of-the-art calibration and validation capabilities assess climate data homogeneity, usually during a scientific campaign. Validation of Aqua, Aura, CloudSat, and CALIPSO data is planned for summer 2007, when the ER-2, WB-57, and DC-8 aircraft, balloon-borne sensors, and enhanced ground-based atmospheric networks will be deployed for simultaneous correlative measurements during the NASA-led Tropical Composition, Cloud, and Climate Coupling (TC4) experiment. TC4 will investigate integrated Earth system processes in convective weather systems over the eastern tropical Pacific and Gulf of Mexico.

ESD will implement an advanced integrated global Earth system model through NASA's new Project Columbia supercomputing facility which, in April 2006, was the fourth fastest in the world. The current version of the model—which will assimilate chemical and physical variables, initially in the atmosphere and then in the ocean—will, for example, simulate global carbon sources and sinks. A new emphasis on cyberinfrastructure through the NASA-led interagency Earth System Model Framework will be initiated.

Related Research

ESD—in partnership with other Federal agencies, State and local governments, academia, and industry—explores new uses of global Earth system observations and science results to mitigate societal problems of national importance. In FY 2007, ESD will complete the benchmark for the assimilation of Aqua, Aura, and Terra observations in the Centers for Disease Control and Prevention (CDC) warning system for airborne particles in Atlanta.

NATIONAL SCIENCE FOUNDATION

Principal Areas of Focus

NSF programs address global change issues through investments in challenging ideas, creative people, and effective tools. In particular, NSF global change research programs support research and related activities to advance the fundamental understanding of physical, chemical, biological, and human systems and the interactions among them. The programs encourage interdisciplinary activities and focus particularly on Earth system processes and the consequences of change. NSF programs facilitate data acquisition and information management activities necessary for fundamental research on global change, and promote the enhancement of models designed to improve understanding of Earth system processes and interactions, and to develop advanced analytic methods to facilitate basic research. NSF also supports fundamental research on the general processes used by organizations to identify and evaluate policies for mitigation, adaptation, and other responses to the challenge of varying environmental conditions. Through its investment, NSF contributes to CCSP by providing a comprehensive scientific foundation for many of the synthesis and assessment products identified in the *CCSP Strategic Plan*.

Program Highlights for FY 2007

Atmospheric Composition

NSF programs in tropospheric and stratospheric chemistry will continue to address the composition of the atmosphere and its relation to climate variability and change. Studies of the transformation and transport of gaseous constituents and aerosols provide insights into the radiative and cloud nucleating properties of the atmosphere. Studies of the global distributions of greenhouse gases will provide input for future scenarios of radiative forcing.

Climate Variability and Change

NSF programs continue to emphasize climate variability and change as a major issue. This research element supports observational campaigns and numerous analytical and modeling activities. Ocean science efforts will focus on changes in ocean structure, circulation, and interactions with the atmosphere to improve current understanding of the processes and models that address future changes, particularly those that may happen abruptly. The Community Climate System Model is being developed to improve model physics and parameterizations that will lead to more comprehensive models incorporating interactive chemistry and biology. Studies of paleoclimatology will continue to be supported as a means to provide baseline data on natural climate variability from the past and from key climatic regions. These studies will improve our understanding of the natural variability of the climate system and in particular will enable reconstructions and evaluations of past environmental change as inputs for model validations.

The Global Water Cycle

NSF supports a broad-based effort to understand all aspects of the global water cycle. Relevant programs will continue to explore ways to optimally and effectively utilize the wide range of hydrological data types—continuous and discrete time and space information from a variety of platforms for research purposes. Information from process studies will be used to refine models through scaling and parameterizations of sub-grid processes, particularly the fluxes of water through the Earth system. Planning for and the initiation of several prototype hydrological observatories, both physical and virtual, are being carried out. Science and Technology Centers will continue to work with stakeholders responsible for water management and with educators to translate research advances into useful products, particularly exploring issues related to decisionmaking in the face of uncertainty as applied to the urbanizing and drought-prone Southwest.

Land-Use and Land-Cover Change

Several NSF programs continue to address key aspects of land-use and land-cover change through studies in ecological rates of change and related species diversity; Arctic systems; temporal variability; water and energy influences on vegetative systems; and diverse human influences on land utilization.

Global Carbon Cycle

NSF supports a wide variety of carbon cycle research activities. Investigations examine a range of topics in terrestrial and marine ecosystems and their relations to the carbon cycle. Research in terrestrial settings will explore, for example, carbon storage, delivery of carbon by rivers, carbon fluxes from high-latitude soils, and carbon export from mountains and submarine groundwater discharge. In the oceans, air-sea gas exchange, remineralization of particles in the mesopelagic, and the upper ocean carbon budget will be addressed. Carbon cycle studies will integrate observational data into models to provide insights for understanding key aspects of the global carbon cycle.

Ecosystems

Several NSF programs address terrestrial and marine ecosystems through observational, experimental, modeling, and laboratory studies. The collection of information and knowledge of climate-ecosystem interactions in terrestrial, freshwater, and marine systems through the Long-Term Ecological Research (LTER) projects derives from the rich array of observation, monitoring, experimentation, and modeling throughout this networked research program. The Hawaii Ocean Times-Series (HOT) and Bermuda Atlantic Time Series (BATS) sites augment the LTER network in the central ocean gyre ecosystems. The Global Ocean Ecosystem Dynamics program will continue to study the impact of global ocean changes on marine ecosystems through specific synthesis activities focused on the North Atlantic, North Pacific, and Southern Ocean systems.

Human Contributions and Responses

NSF supports basic research on the processes through which people (individually, in groups, or through organizations) interact with natural environmental systems. Programs support projects that focus on decisionmaking under uncertainty associated with climate change. These projects are expected to produce new knowledge and tools that should facilitate improved decisionmaking by various stakeholder groups trying to deal with uncertainties associated with future climate variability and change.

International Research and Cooperation

The "International Polar Year 2007-2008" (IPY) will extend from March 2007 through March 2009. The President's Office of Science and Technology Policy designated NSF the lead Federal agency in organizing U.S.-International Polar Year activities. NSF IPY activities will focus on improving our understanding of climate change in the Arctic and on longer term sea-level changes associated with changes in the stability of the Greenland and Antarctic ice sheets.

Related Research

NSF will continue to support "contributing" research on broader topics that are closely related to global and climate change. These include, *inter alia*, studies of the atmosphere, ocean, land surface, ecosystems, paleoclimatology, and human dimensions—all of which add substantively to the specific programs supporting CCSP objectives. NSF has the computing infrastructure in place and under enhancement to enable more effective utilization of the research information. In addition, NSF supports projects that integrate research with education on global and climate change to demonstrate that scientific visualization—incorporated into inquiry-based learning—can enable students to develop an understanding of complex global change phenomena. Students address these issues by evaluating multimedia data at various spatial and temporal resolutions, reviewing scientific evidence, and considering social concerns that contribute to global and climate change debates.

SMITHSONIAN INSTITUTION

National Air and Space Museum (NASM)
National Museum of Natural History (NMNH)
National Zoological Park (NZP)
Smithsonian Astrophysical Observatory (SAO)
Smithsonian Environmental Research Center (SERC)
Smithsonian Tropical Research Institute (STRI)

Principal Areas of Focus

Within the Smithsonian Institution, global change research is conducted at the Smithsonian Astrophysical Observatory, the National Air and Space Museum, the Smithsonian Environmental Research Center, the National Museum of Natural History, the Smithsonian Tropical Research Institute, and the National Zoological Park. Research is organized around themes of atmospheric processes, ecosystem dynamics, observing natural and anthropogenic environmental change on daily to decadal time scales, and defining longer term climate proxies present in the historical artifacts and records of the museums as well as in the geologic record at field sites. The Smithsonian Institution program strives to improve knowledge of the natural processes involved in global climate change, to provide a long-term repository of climate-relevant research materials for present and future studies, and to bring this knowledge to various audiences, ranging from scholarly to the lay public. The unique contribution of the Smithsonian Institution is a long-term perspective—for example, undertaking investigations that may require extended study before producing useful results and conducting observations on sufficiently long (e.g., decadal) time scales to resolve human-caused modification of natural variability.

Program Highlights for FY 2007

Atmospheric Composition

At SERC, measurements will be made of spectral UV-B in Maryland (>25-year record), Florida, Arizona, and other sites in the United States. These data will be electronically disseminated to meet the needs for assessing the biological and chemical impact of varying ultraviolet radiation exposures.

Climate Variability and Change

Research at NASM will emphasize the use of remote-sensing data to improve theories of drought, sand mobility, soil stability, and climate change in the eastern Sahara. Studies at NMNH and STRI will focus on the paleoecology of climate change.

Terrestrial and Marine Ecosystems

Several Smithsonian programs will examine biological responses to global change. At SERC, research will be conducted on the responses of global ecosystems to increasing carbon dioxide concentrations (also a contribution to the Global Carbon Cycle program). This SERC program will also focus on invasive species and solar UV-B. Biodiversity education and research will be performed at STRI, NMNH, and NZP. Tropical biodiversity research programs monitor global change effects through repeated sampling of flora and fauna in tropical forests, and identifying the physical and biological processes of growth and decline of species. Other studies on ecosystem response to increasing habitat fragmentation will be conducted at NZP.

Human Dimensions of Global Change

The general public and research community will be informed of global change research conducted by Smithsonian and other CCSP agencies via exhibits. During FY 2007, exhibits developed by staff at NMNH, SERC, and SAO will be displayed at NMNH in the "Forces of Change: Global Links" series concerning the atmosphere and the Arctic, with accompanying educational programs and ancillary information accessible through the Internet.

Related Research

Much of the global change research performed at the Smithsonian is not supported by direct Federal appropriation (i.e., CCSP cross-cut funding) and instead is supported by other public and private sources (including other CCSP-participating agencies). These projects are nonetheless organized around the CCSP program elements, thus amplifying the scope and impact of research supported directly by CCSP. At SAO, there are extensive measurement programs for stratospheric and tropospheric composition. These include pollution measurements from space and its eventual development into continuous global monitoring. This work contributes to global climate observations, enhances climate modeling systems, quantifies greenhouse gas sources and sinks, and reduces scientific uncertainties of aerosol effects. There are continuing studies on solar activity and its relationship to climate. SERC and STRI receive agency support via competitive grants programs to perform studies of ecosystem responses to increased carbon dioxide, UV-B, and invasive species. Other contributing activities include research conducted by several units within the Smithsonian in a variety of habitats concerning natural and human-induced variations in species, populations-communities, and ecosystems. These studies help clarify the relative importance of global change effects as one of several agents of ecological change. Studies of environmental change over long time periods are aided by the Institution's collections. Used by researchers around the world, these materials provide raw data for evaluating changes in the physical and biological environment that occurred before human influences.

N O T E S

NOTES

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