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.

Carbon is important as the basis for the food and fiber that sustain and shelter human populations, as the primary energy source that fuels economies, and as a major contributor to the planetary greenhouse effect and potential climate change. Carbon dioxide (CO_2) is the largest single forcing agent of climate change, and methane (CH_4) is also a significant contributor.

Atmospheric concentrations of CO_2 and CH_4 have been increasing for about two centuries as a result of human activities and are now higher than they have been for over 400,000 years. Since 1750, CO_2 concentrations in the atmosphere have increased by 30% and CH_4 concentrations in the atmosphere have increased by 150%.

Approximately three-quarters of present-day anthropogenic CO_2 emissions are due to fossil fuel combustion (plus a small amount from cement production). Land-use change accounts for the rest. The strengths of CH_4 emission sources are uncertain due to the high variability in space and time of biospheric sources. Future atmospheric concentrations of these greenhouse gases will depend on trends and variability in natural and human-caused emissions and the capacity of terrestrial and marine sinks to absorb and retain carbon.

Decisionmakers searching for options to stabilize or mitigate concentrations of greenhouse gases in the atmosphere are faced with two broad approaches for controlling atmospheric carbon concentrations: 1) reduction of carbon emissions at their source—such as through reducing fossil fuel use and cement production or changing land use and management (e.g., reducing deforestation); and/or 2) enhanced sequestration of carbon—either through enhancement of biospheric carbon storage or through engineering solutions to capture carbon and store it in repositories such as the deep ocean or geologic formations.

Enhancing carbon sequestration is of current interest as a near-term policy option to slow the rise in atmospheric CO_2 and provide more time to develop a wider range of viable mitigation and adaptation options. However, uncertainties remain about how much additional carbon storage can be achieved, the efficacy and longevity of carbon sequestration approaches, whether they will lead to unintended environmental consequences, and just how vulnerable or resilient the global carbon cycle is to such manipulations.

Successful carbon management strategies will require solid scientific information about the basic processes of the carbon cycle and an understanding of its long-term interactions with other components of the Earth system, such as climate and the water and nitrogen cycles. Such strategies also will require an ability to account for all carbon stocks, fluxes, and changes and to distinguish the effects of human actions from those of natural system variability. Because CO_2 is an essential ingredient for plant growth, it will be essential to address the direct effects of increasing atmospheric concentrations of CO_2 on terrestrial and marine ecosystem productivity. Breakthrough advances in techniques to observe and model the atmospheric, terrestrial, and oceanic components of the carbon cycle have readied the scientific community for a concerted research effort to identify, characterize, quantify, and project the major regional carbon sources and sinks—with North America as a near-term priority.

The agencies responsible for CCSP carbon cycle research (DOE, NASA, NIST, NOAA, NSF, USDA, and USGS) have planned a coordinated, interagency, and multidisciplinary research strategy to bring together the broad range of needed infrastructure, resources, and expertise essential for providing this information. A continuing dialogue with stakeholders—including resource managers, policymakers, and other decisionmakers—will be established and maintained to ensure that desired information is provided in a useful form.

Highlights of Recent Research

Highlights of recent research supported by CCSP participating agencies follow.

Recent trends in greenhouse gases quantified. Based on monitoring since the late 1970s, data from more than 50 global sites of the Global Cooperative Air Sampling Network show continuing increases in the atmospheric concentrations of CO_2, CH_4, nitrous oxide (N_2O), and other greenhouse gases. Percentage increases of CO_2 and N_2O are similar. The methane increase has slowed considerably, and the most

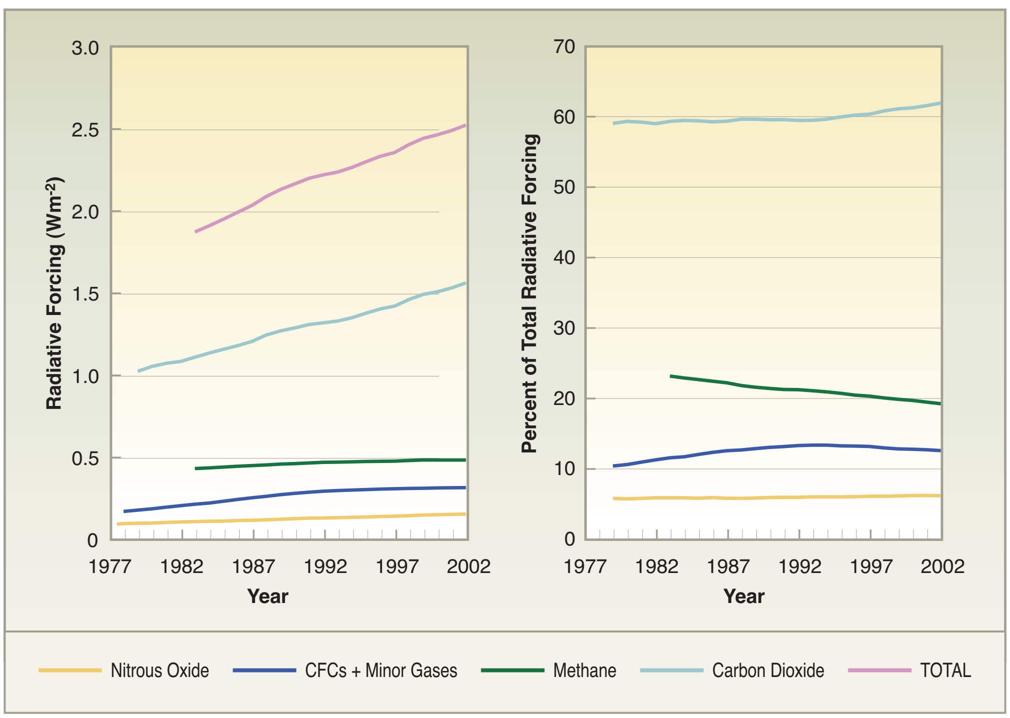


Figure 18: Radiative climate forcing by long-lived greenhouse gases. Direct radiative forcing (in Wm^{-2}) by four classes of major long-lived greenhouse gases (left panel), and percentage of the total direct forcing for each of the four (right panel). Annual averages are from NOAA's Global Cooperative Air Sampling Network. *Credit: NOAA Climate Monitoring and Diagnostics Laboratory.*

recent measurements indicate it has leveled off. CO_2 accounts for more than 60% of the calculated direct radiative forcing for these gases, and CH_4 is now less than 20% (see Figure 18). The time-averaged atmospheric CO_2 concentration increase has been approximately 1.5 ppm per year over the past several decades. While there is large year-to-year variation, and a very small annual rate of increase, 1.5 ppm per year would be most appropriate for use as the CO_2 forcing in current climate modeling applications.

AmeriFlux measures terrestrial carbon sinks. Measurements of the net exchange of CO_2 between terrestrial ecosystems and the atmosphere—referred to as net ecosystem exchange (NEE)—confirm that most terrestrial ecosystems in the United States are assimilating CO_2 and are important sinks for atmospheric CO_2. While NEE measures vary according to properties of ecosystems and their environments, over a 3- to 10-year period of observation annual net carbon uptake ranged from 2 to 4 tons per hectare for forests, and about 1 ton or less per hectare for agriculture and grassland. In addition to the unique NEE results, AmeriFlux sites are producing systematic biological and micro-meteorological data for understanding both terrestrial carbon cycling processes and the biophysical controls on them.

Climate-driven increases in terrestrial productivity. New analyses of 18 years of climatic data and satellite observations of vegetation indicate that changes in climate have eased several critical climatic constraints to plant growth around the world. Global terrestrial net primary productivity has increased 6% (3.4 PgC over 18 years), with 25% of the global land area showing significant increases and 7% showing significant decreases (see Figure 19). Ecosystems in all tropical regions and in the high latitudes of the Northern Hemisphere accounted for 80% of the increase in

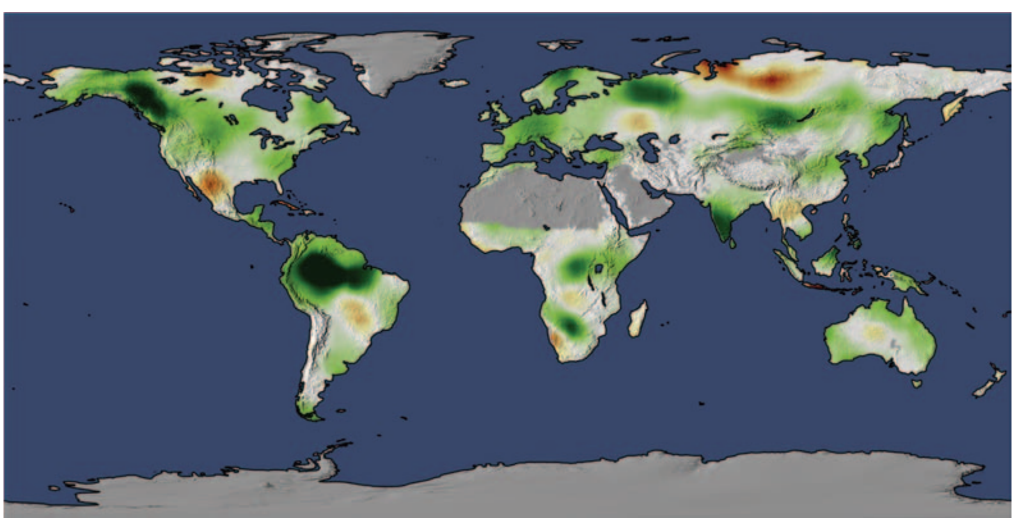


Figure 19: Global change in terrestrial net primary productivity (NPP), 1982-1999. NPP was calculated using mean fraction of absorbed photosynthetically active radiation and leaf area index derived from two different Advanced Very High-Resolution Radiometer (AVHRR) data sets. Areas of increase in NPP are colored green and areas of decrease in brown. *Credit: R. Nemani, NASA Ames Research Center [first presented in Science, **300**, 1560-1563 (6 June 2003)].*

productivity. Tropical increases were attributed to decreased cloud cover and the resulting increase in solar radiation. Increases in other regions were due to the combined effects of increasing temperature, changes in rainfall, and changes in solar radiation.

Conservation Reserve Program (CRP) lands removing greenhouse gases from the atmosphere. Results across a 13-state region of the United States show that CRP lands sequester about 910 kg of carbon per hectare in the top 20 cm of soil each year. This translates to 5.1 million metric tons of carbon removed from the atmosphere and sequestered into the soil each year in the 5.6 million hectares (about 13.8 million acres) of CRP land. The research demonstrates a clear role for farmers and ranchers in carbon sequestration and possibly climate change mitigation—in addition to the conventional CRP benefits of improving soil, water, and wildlife resource conservation.

Ocean Inventory of Anthropogenic Carbon. Estimates of the current oceanic anthropogenic CO_2 inventories and transports have been greatly improved using data from the global surveys of the World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux Study (JGOFS), and the Ocean Atmosphere Carbon Exchange Study (OACES). Between 1991 and 1998, these programs produced a large number of high-quality measurements of important tracers for anthropogenic carbon, including nearly 100,000 dissolved inorganic carbon (DIC) samples as well as a large number of other high-quality measurements of important anthropogenic carbon tracers such as chlorofluorocarbons (CFCs), ^{13}C and ^{14}C of DIC, and other chemical species important in the study of biogeochemical cycling.

Analyses of these data indicate a total uptake of approximately 117 $\pm$ 19 PgC from anthropogenic sources and large regional differences in its horizontal and vertical distribution in the world's oceans. The reconstructed distribution of anthropogenic CO_2 in the oceans shows large differences between the North Atlantic, where anthropogenic CO_2 can be traced down to the bottom, and the tropical Pacific, where no anthropogenic CO_2 can be detected below 600 m. Despite the predominantly Northern Hemisphere source of fossil fuel CO_2, approximately 60% of the anthropogenic CO_2 is located in the Southern Hemisphere associated with the subtropical convergence zones (see Figure 20). This distribution is consistent with that expected based on current knowledge of large-scale ocean circulation.

Effect of climate variability on air-sea exchange of CO_2. Measurements from studies in the Equatorial Pacific Ocean show a large shift in the surface water partial pressure of CO_2 (pCO_2) levels and CO_2 fluxes to the atmosphere from the 1980s to the 1990s. The surface water pCO_2 levels increased much more slowly in the 1980s than in the 1990s, with the change in trend occurring around 1990. This timing

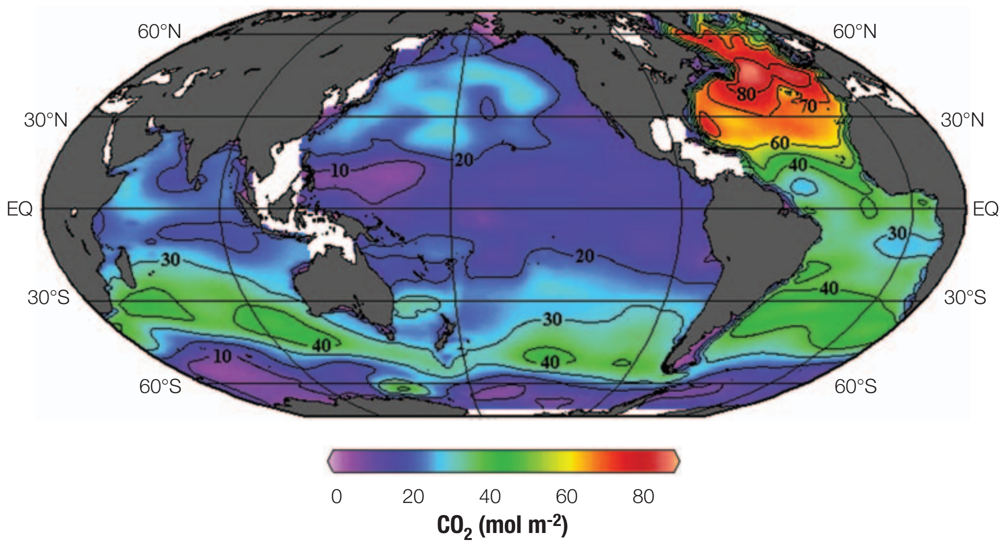


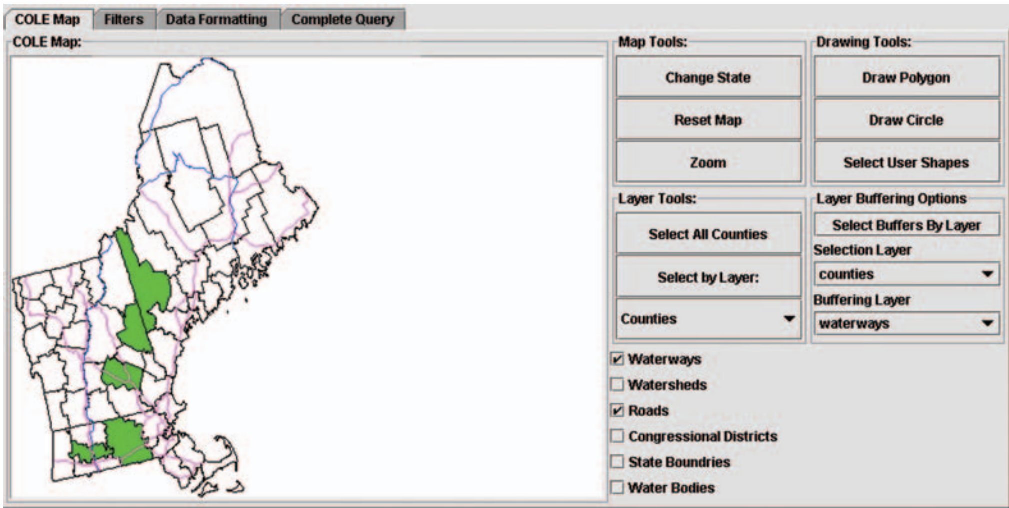
Figure 20:
Distribution of anthropogenic CO_2 in the global oceans through 1994. Between 1991 and 1998, global ocean CO_2 surveys produced a large number of high-quality measurements of important tracers for anthropogenic carbon. Estimates of the anthropogenic CO_2 uptake based on the observations indicate a total anthropogenic CO_2 inventory of approximately 117 ± 19 PgC in 1994. *Source: Sabine, C.L., et al., Chapter 2: Current status and past trends of the global carbon cycle. In Toward CO_2 Stabilization: Issues Strategies, and Consequences [C.B. Field and M.R. Raupach (eds.)], Island Press, Washington D.C. [in press].*

corresponds with a change in the Pacific Decadal Variability and is consistent with the hypothesis that natural climate variations have a major effect on air-sea CO_2 fluxes. This is the first documentation of an effect on the ocean carbon system by a time scale oscillation with a periodicity longer than that of the El Niño-Southern Oscillation (ENSO).

Ocean color calibration refinement improves carbon estimates. Observed ocean color variability, as measured by satellites, was modified based upon new radiometric characterizations of the *in situ* calibration sensors on the Marine Optical Buoy (MOBY), which is used for on-orbit calibration of satellite sensors such as SeaWiFS and MODIS. A new, portable, tunable-laser system was used to improve characterization of the MOBY sensors, and a new algorithm was developed to correct for stray light effects. These adjustments have improved SeaWiFS calibration, resulting in reductions in derived global mean chlorophyll concentrations of about 6%, which, in turn, reduced global ocean biomass and primary productivity estimates, yielding a more accurate understanding of the oceans' role in Earth's carbon budget.

Carbon On-Line Estimation (COLE). A new computer tool has been developed to provide forest carbon estimates for user-defined areas of the conterminous United States. The project is an effort to make forest inventory analysis data readily accessible. COLE should allow the user to harness these data and use them in a number of complex queries involving estimates of sequestered carbon. COLE gives the user an interactive, on-line database query capability, and has been implemented with a database for the eastern United States (see Figure 21).

Figure 21: The USDA Forest Service's Carbon On-Line Estimation graphical analysis tool provides an interactive, on-line database query capability. A beta version of the program estimates carbon stocks based on the USDA Forest Service Eastwide Forest Inventory database. The program allows the user to designate an area of interest, and currently provides growing stock volume, areas, and carbon stocks for States east of the Great Plains in tabular, graphical, or map format. *Credit: USDA Forest Service.*



Disturbance and seasonal dryness reverse seasonality of carbon exchange in moist tropical forests. Recent results from eddy covariance flux and biometric measurements in two old-growth Amazonian forests indicate that the seasonality of carbon exchange is exactly the opposite of what conventional knowledge and models predict. Carbon was lost during the 7-month wet season and gained during the 5-month dry season. The short dry season strongly limits respiration due to desiccation of surface detrital materials, but only weakly affects photosynthesis because there is adequate moisture at depth. Decomposition of the large amounts of coarse woody debris in these forests, present due to past disturbances, predominates after the rains resume. These are also the first eddy covariance measurements that document a net carbon loss to the atmosphere from old-growth forests in the Amazon.

Highlights of FY 2004 and FY 2005 Plans

The U.S. carbon cycle science program will continue to focus on understanding and quantifying global carbon sources and sinks, with a particular emphasis on North America and adjacent oceans for the near term, and on filling critical gaps in understanding in order to reduce major uncertainties about the global carbon cycle. Special attention will be paid to carbon management and carbon cycle processes that can cause significant changes in the size and longevity of important carbon sources and sinks on land and in the ocean.

In the next 2 years, emphasis will be on implementing the North American Carbon Program (NACP) and the Ocean Carbon and Climate Change (OCCC) plans developed through the auspices of the Carbon Cycle Science Steering Group. Program coordination and data management infrastructure will be established and new opportunities will be made available to conduct research in these areas. A strategy for conducting intensive research within the NACP will be communicated in 2004, and the first of these intensive field research programs and/or campaigns will be underway in 2005. Key research plans for FY 2004 and FY 2005 follow.

Systematic observations in the North American Carbon Program. In order to reduce the uncertainty in North American carbon sources and sinks, measurement networks are being installed and enhanced across the United States. The networks include AmeriFlux and AgriFlux sites, tall (500 m) towers, vertical atmospheric carbon profiling stations, and ocean platforms. In addition, a new tier of measurements at the landscape scale (landscape monitoring) will be initiated and evaluated. Systematic data from these networks will be merged with satellite observations to provide an integrated and consistent result and a framework for continental-scale synthesis and modeling of carbon sinks and sources. Specific activities include:

- Flux and atmospheric CO_2 concentration measurements will be upgraded at selected AmeriFlux and AgriFlux sites to support planned NACP intensive field research, regional atmospheric studies, and national inventories.
- Atmospheric profiling and flux measurements by aircraft and tall towers will be expanded to about 15 stations by the end of 2004 in preparation for NACP intensive research and to test integrated sampling protocols at regional and continental scales and methods for data assimilation and modeling.
- Air-sea CO_2 exchange measurements in the North Atlantic and North and Equatorial Pacific Oceans will be made to help define boundary conditions for improved modeling of North American carbon sources and sinks.
- Robust *in situ* sensors will be developed to better calibrate coastal ocean color data from satellites and improve coastal carbon source and sink quantification.
- New Earth Observing System satellite data products will be developed. The data products will be customized for analyzing primary productivity, land cover, and carbon dynamics in North America and adjacent oceans. The first of these data products will be made available in 2005; they will be used for spatial extrapolation and scaling and/or for driving carbon models. Regional studies to integrate remote-sensing data with forest inventory, water monitoring, and historical land-use change data to quantify carbon sources and sinks will be underway in 2004.
- A new measurement tier at the landscape scale will be initiated using an intermediate set of biometric measurements to link between the extensive monitoring of inventories and remote sensing and the intensive monitoring of flux towers, process studies, and manipulative experiments. This landscape-monitoring tier will include clusters of measurement sites that represent conditions over large landscapes. A study design has been developed and reviewed, and three pilot studies to evaluate the design will be implemented during 2004 and 2005.

These activities will address Question 7.1 (second of the milestones, products, and payoffs) and 7.4 (first of the milestones, products, and payoffs) of the CCSP Strategic Plan.

Intensive field research and campaigns in the NACP. In order to achieve the goals of the NACP, one or more intensive field research projects or campaigns will be needed to evaluate methodological approaches and test key hypotheses. These 'intensives' will be focused on specific, challenging issues that are critical to the success of the overall NACP, that require unusual concentrations of resources, and that are time-sensitive (i.e., lack of progress on this issue hinders major elements of the program). Each of these intensives will require especially close interagency cooperation and multidisciplinary research approaches. The first intensives to be conducted will be decided in 2004 and will be underway by 2005.

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

Carbon storage by crop and rangelands. Inventory and analytical studies will provide data on the extent to which commonly used soil management systems across the United States remove CO_2 from the atmosphere and store it in croplands and rangelands.

These activities will address Questions 7.1, 7.3, and 7.6 (first of the milestones, products, and payoffs) of the CCSP Strategic Plan.

Repeat hydrography CO_2/tracer measurement and new transport studies. CO_2 inventory and transport studies will be conducted in the North Atlantic and North Pacific Ocean to determine decadal changes in physical and biogeochemical process affecting the distribution of CO_2 in the oceans and to estimate anthropogenic carbon uptake in the basins. Additionally, new research will be initiated in 2004 on carbon transport and fate from drainage basins to ocean margins.

These studies will address Questions 7.1 and 7.2 of the CCSP Strategic Plan.

Underway pCO_2 measurements in the North Atlantic and North Pacific. Measurements of surface ocean pCO_2 will be implemented on research and volunteer observing ships as they are underway to quantify the seasonal and interannual variations of air-sea CO_2 fluxes in the ocean basins adjacent to North America.

These measurements will address Questions 7.1 and 7.2 of the CCSP Strategic Plan.

Relationships among climate, phytoplankton, carbon, and iron in the Antarctic Ocean. New studies will be conducted to assess the role of the Antarctic Ocean in absorbing atmospheric CO_2, as well as the role of iron in regulating ocean carbon cycle processes.

These studies will address Questions 7.2 and 7.5 of the CCSP Strategic Plan.

Seasonal and interannual ocean productivity patterns. Multiple overlapping and consecutive measurements of phytoplankton chlorophyll *a* and estimates of primary productivity from satellite sensors (OCTS, SeaWiFS, and MODIS) will be linked in an 8-year or longer time series, with new data to be added as it is collected. These consistent time series of data will become available in 2005. They will be used to examine seasonal to interannual patterns of change, improve models, and reduce errors in estimates of carbon sources and sinks.

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

Carbon cycle modeling. Advanced modeling research will be initiated in 2004 to improve regional- and continental-scale carbon models. Improved models of ocean margin productivity and coastal carbon cycling processes will be developed. New data assimilation approaches, employing both *in situ* and satellite observations, and improved land-atmosphere-ocean coupling, will be emphasized. Improved characterization of multiple, interacting process constraints also will be pursued.

These activities will address Questions 7.1 (fifth of the milestones, products, and payoffs), 7.2, and 7.5 (third and fourth of the milestones, products, and payoffs) of the CCSP Strategic Plan.

Greenhouse gas accounting rules and guidelines for forest systems and agricultural soils. In response to a Presidential directive, greenhouse gas accounting rules and guidelines for forest systems and agricultural soils will be developed for crediting forestry and agriculture sequestration projects, which is part of the Climate Change Research Initiative. Guidelines will provide for consistent reporting of carbon sequestration estimates by region and management intensity. Technical guidance and software will aid measurement and computation of carbon content of standing stocks as well as soils and wood products. The goal is to base greenhouse gas accounting guidelines on sound scientific information and to illustrate added value that carbon credits might bring to traditional forestry. Rules and guidelines will be available in 2005.

These activities will address Questions 7.1 (first of the milestones, products, and payoffs), 7.3, and 7.6 of the CCSP Strategic Plan.

Orbital Carbon Observatory (OCO). OCO will make space-based measurements of atmospheric CO_2 (total column) that will greatly improve the accuracy and resolution of the inverse atmospheric transport models used to characterize carbon sources and sinks. OCO was confirmed for mission formulation in 2003, and during 2004 and 2005 it will proceed through a series of important design and mission confirmation reviews. It is scheduled for a 2007 launch.

This activity will address Questions 7.4, 7.5, and 7.6 of the CCSP Strategic Plan.

Prototype State of the Carbon Cycle report. The first CCSP synthesis and assessment product related to carbon cycle science will be delivered in 2005. The topic is the North American carbon budget and implications for the global carbon cycle—providing an evaluation of our knowledge of carbon cycle dynamics relevant to the contributions of and impacts on the United States, and scientific information for U.S. decision support focused on key issues for carbon management and policy.

This activity will address Questions 7.1 (last of the milestones, products, and payoffs), 7.2, and 7.4 of the CCSP Strategic Plan.