# Chapter 3: Predicting the Future Carbon Cycle

The previous chapter addressed the first of the two overarching questions that the Carbon Cycle Science Plan (CCSP) must attempt to answer. In this chapter, we turn to the second of the two fundamental issues for carbon cycle research:

***What will be the future atmospheric carbon dioxide concentrations resulting from both past and future emissions?***

The research program outlined in this report will ultimately be measured by its ability to provide reliable estimates of future atmospheric $CO_2$ concentrations under different conditions. Only with such knowledge will it be possible to assess alternative scenarios of future emissions from fossil fuels, effects of human land use, sequestration by carbon sinks, and responses of carbon cycling to potential climate change. Thus, the foremost reason for additional research is to develop the ability to predict responses of the global carbon cycle to various types of change. The CCSP must be integrated in the form of a rigorous and comprehensive effort to build and test models of carbon cycle change, to evaluate and communicate uncertainties in alternative model simulations, and to make these simulations available for public scrutiny and application. The models must also be capable of evaluating alternative scenarios for management of the carbon cycle.

There are grounds for optimism that in coming years the fate of $CO_2$ in the ocean can be ascertained with reasonable accuracy. The global mass balance among emissions, atmosphere, ocean, and terrestrial biosphere ensures that a better quantitative estimate of ocean uptake also improves the estimate for changes in terrestrial storage, if only in very coarse geographical detail. Direct measurements of terrestrial inventories and fluxes, in conjunction with atmospheric measurements and models, will help to refine the geographical details.

Unfortunately, improved knowledge of the environmental fate of historical $CO_2$ emissions cannot by itself give us confident predictions of future atmospheric $CO_2$. The $CO_2$ concentration trajectories calculated by the Intergovernmental Panel on Climate Change (IPCC) for scenarios of fossil fuel burning assume that the future carbon cycle will continue operating exactly as it is thought to have operated in the past. This assumption is not likely to be correct.

There is a fundamental difference between the ocean and the terrestrial biosphere for policy decisions relating to greenhouse gases. The ocean remains the biggest long-term player in the carbon cycle, and any research program that neglects the ocean is doomed to be nearly irrelevant for policy. However, direct human interventions in the ocean carbon cycle have thus far been minimal. Furthermore, any future human interventions, such as direct injection of $CO_2$ in the deep ocean or enhancement of the biological flux of carbon by fertilization, will likely be dwarfed by the magnitude of the ongoing passive uptake. On the other hand, humanity is already manipulating the terrestrial biosphere on a global scale, and its influence on atmospheric $CO_2$ is substantial. The effect on the carbon cycle of ecological interventions on land has been mostly inadvertent to date. Most of the interventions have resulted in decreasing the amount of carbon in various terrestrial carbon reservoirs. In particular, woody biomass and active soil organic matter, because of their intermediate turnover times (30 to 100 years), are the largest terrestrial pools affected by land use conversion and agricultural establishment. This past reduction in terrestrial carbon storage, however, suggests the opportunity to increase carbon in terrestrial systems through intentional management. The realization that sequestration of carbon in wood and soil may play a significant role in offsetting $CO_2$ from fossil fuel burning is already evident in international negotiations.

Concerning how high atmospheric $CO_2$ might go in the future, two general questions must be answered:

- ***What will be the partitioning of carbon among the mobile reservoirs, and how will climate change affect this partitioning?***
- ***How can the future growth of atmospheric $CO_2$ be managed?***

Each of these points is examined, and thereafter, a major new research initiative is proposed to address the most compelling scientific issues, an initiative that is also scientifically feasible and cost-effective.

## Projecting Future Atmospheric $CO_2$ Concentrations

The IPCC has provided some scientific basis for international policy decisions by extrapolating the historical behavior of the terrestrial biosphere and ocean into the future. Again, the assumption is that carbon uptake by the terrestrial biosphere will continue to occur through the same mechanisms as at present, and that ocean circulation and biology will remain constant through time (Houghton et al. 1996). However, from coupled atmosphere-ocean simulations with time-dependent radiative forcing (e.g.,Haywood et al.1997),it appears possible that the terrestrial biosphere and ocean carbon cycle might already be experiencing direct effects of climate change today. These effects could become even larger over the next century (e.g.,Cao and Woodward 1998,Sarmiento et al.1998). Further, it seems likely that both terrestrial and oceanic ecosystems will undergo significant indirect responses to climate change and human impacts on the environment, such as $NO_x$ [nitrogen oxides] fertilization,air and water pollution,and $CO_2$ increase. Such shifts might include changes in species distribution in addition to changes in the supply of nutrients and other ecosystem components that determine carbon cycling.

## *Terrestrial Ecosystems*

Terrestrial ecosystems have played and will continue to play a significant role in the global carbon cycle. Release of $CO_2$ from land use change has been a significant flux to the atmosphere historically, and could well continue or even accelerate. In addition,there appears to be a significant sink of $CO_2$ in land ecosystems arising from the synergistic effects of past land use changes,increasing atmospheric $CO_2$, the deposition of fixed nitrogen,and,possibly, climate changes over the past century or so. To project the consequences of given human activities (such as fossil fuel burning and land use change),it is essential to understand the responses of terrestrial ecosystems. It is likewise important to understand how climate interacts with terrestrial ecosystems. Several factors will control the balance of terrestrial ecosystems with respect to carbon. The current degree of uncertainty regarding all of these factors is high.

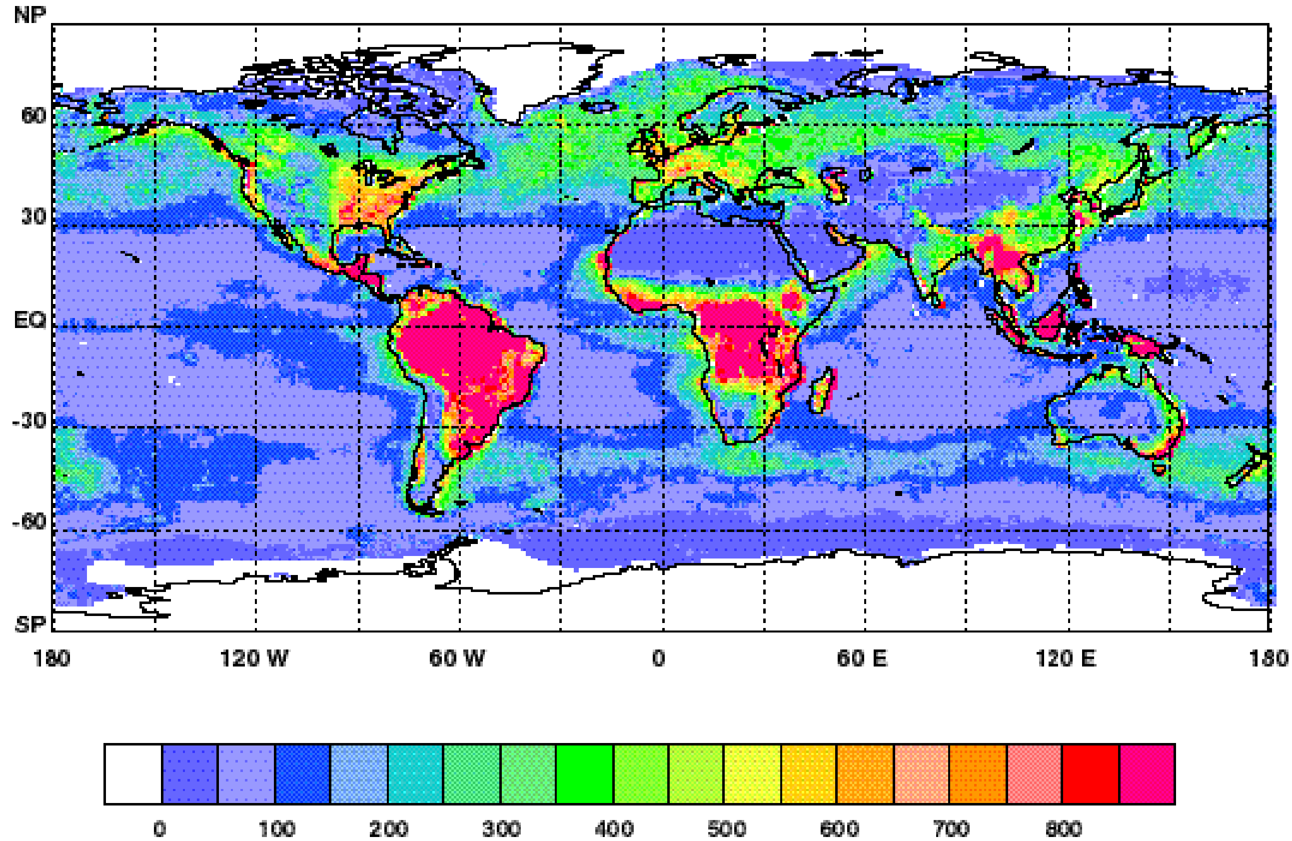
Increasing $CO_2$ and fixed nitrogen from fossil fuel burning can both act as fertilizers to ecosystems,increasing net primary production (NPP, the amount of carbon processed by photosynthesis in green plants minus that lost through respiration),and possibly carbon storage. Air and water pollution can lead to degradation of the ecosystem and loss of carbon. Observational and manipulative studies have not yet yielded unambiguous results about the magnitudes of these effects,and there are thus substantial disagreements in model predictions.

There is evidence that climate change and variability over the past century may have influenced both the distribution of vegetation and its productivity. The potential exists for significant positive climate feedback in which warming of arctic soils and permafrost,high in organic carbon content,could stimulate the oxidation to $CO_2$ of much of that carbon (Goulden et al.1998,Oechel et al. 1993). Most models of vegetation dynamics suggest possible major redistribution of vegetation zones with future climate change. Changes in the extent of ecosystems such as carbon-rich peatlands and forests or carbon-poor deserts could substantially affect carbon storage on land. Although slow changes to long-lived vegetation are difficult to study experimentally, and models of these processes are in early developmental stages,an integrated program of manipulative experiments,paleoecological studies,and continuing observations can facilitate continuing improvements in the models.

Significant integrative research is needed to improve predictive capability for terrestrial ecosystems,both managed and natural. First,the basic science and its representation in models must be improved. Better representation is needed of key processes,such as responses to disturbances,$CO_2$ warming, nutrient deposition,and atmospheric pollution,including their interactions. Important questions are emerging that require new direct evidence from observational and manipulative studies. Analyses of atmospheric observations also require better models of terrestrial ecosystems. Models are an important tool in inverse analysis of atmospheric data (inverse analysis is a mathematical tool that infers unknown variables from a given set of equations,data and assumptions).Models of the land biosphere are urgently needed for data analysis. Beyond global models,detailed site-specific models are also required to assess the long-term consequences of management options. Such models can be used to appraise the influence of a given forest or agricultural management practice on both commodity production and environmental impacts at the same time,including carbon storage and trace gas exchange. Improving projections of the future carbon balance of terrestrial ecosystems requires an integration of global carbon cycle and climate models (to calculate climate-ecosystem feedbacks on atmospheric $CO_2$) and management-oriented models for use in decision making about terrestrial ecosystems. Decisions about terrestrial ecosystems will influence—perhaps heavily—the future effects of ecosystems on the atmosphere.

## *The Ocean*

Coupled atmosphere-ocean model simulations (e.g., Haywood et al. 1997) predict a large warming of the surface waters of the ocean (e.g., of 2.5°C by mid next century). They also predict increased stratification of the surface ocean from the higher temperature at low latitudes and increased precipitation in high latitudes. One of the consequences of these changes may be a reduced rate of formation of North Atlantic Deep Water, perhaps as early as the next decade. However, on time scales of a few decades, changes in the rate of convection and vertical mixing appear more important for the surface $CO_2$ balance than changes in advection. Further, in at least one simulation, ocean $CO_2$ uptake is particularly impacted by changes




***Global, annual net primary production (NPP) (g C/m$^2$/y) for the land and ocean biosphere. This calculation is from models that use satellite data to calculate the absorption of visible radiation by photosynthetic pigments in plants, algae, and cyanobacteria. The land model (CASA) and the ocean model (VGPM) are similar in their reliance on broadly observed patterns to scale photosynthesis and growth from the individual to the ecosystem level. This calculation, based on ocean data for 1978–1983 and land date for 1982–1990 produces a global NPP of 104.9 Pg C/y (104.9 x 10$^{15}$ g C/y), with approximately half (46.2%) contributed by the oceans and half (53.8%) contributed by the land. These approximately equal contributions to global NPP highlight the role of both land and ocean processes in the global carbon cycle.***

in the Southern Ocean compared with other regions of the ocean. These changes in ocean mixing and circulation may reduce cumulative oceanic uptake of $CO_2$ by 10 to 30 percent between now and the middle of the next century (Matear and Hirst in press, Sarmiento et al. 1998).

Climate change may also have a major impact on ocean biology, which in turn would affect the ocean's uptake of $CO_2$. One change may be reduced or altered global productivity due to slower upward mixing of nutrients from the thermocline, or increases in productivity associated with anthropogenic nutrients or richer supply of micronutrients by dust transport. Another may be change in taxonomic composition and physiology. Environmental changes that could drive such ecological shifts include warming of surface waters and stabilization of the water column. The supply of micronutrients by dust transport has an important impact on ecology, as in making it possible for nitrogen fixers to exist in nutrient-poor regions (Michaels et al. 1996a). Also important are carbon chemistry changes. The concentration of carbonate ion will decrease by 30 percent and the pH by more than 0.2 in the mixed layer by the middle of the next century. Some changes in taxonomic composition and bulk physiology could have an impact on important carbon cycle parameters. Among these are the ratio of calcium carbonate ($CaCO_3$) to organic carbon production in coral reefs (Smith and Buddemeier 1992) and coccolithophorids, the ratio of organic carbon to nutrients in material exported from the surface, and the amount of carbon locked up as dissolved organic carbon, which presently amounts to about 90 billions of metric tons, or 90 gigatons (Gt C), in the upper 500 meters.

Time-series observations from the past decade show clearly that ocean biota respond dramatically to interannual climate variability such as the El Niño–Southern Oscillation (ENSO) (Karl 1999). Ocean warming due to climate change could lead to changes of comparable magnitude. Simulations with ocean general circulation models show that biological changes may increase the oceanic uptake of $CO_2$ by 5 to 25 percent, depending on what

**assumptions are made about how to model the biological response. This effect is large enough to counteract much if not most of the reduction in uptake from mixing and circulation, but the magnitude and even the sign of this effect are highly uncertain.**

**The relationship between marine ecosystem structure and the rate at which biological processes move carbon between surface and deep waters is an emerging research theme. The most prevalent ecosystem structure of the open sea, particularly in the equatorial and subtropical regions, is one dominated by the microbial loop. The microbial loop consists of very small organisms in a complex trophic structure with efficient nutrient recycling, little accumulation of biomass, and little export of carbon from surface waters to the deep sea (Landry and al.1997). Experimental evidence (e.g., Coale et al.1996) shows that nutrient perturbations to the steady state in these ocean regions leads to enhanced growth and dominance of diatoms and other large phytoplankton. Increased new production associated with diatom blooms, for example, increases carbon dioxide uptake from the atmosphere in surface waters and (eventually) leads to vertical export of particulate carbon to deep waters.**

**At high latitudes, and particularly in the Southern Ocean, increased stratification in response to climate change may lead to a more efficient biological export of carbon from surface to deep waters, thereby reducing surface nutrients and carbon. The evidence for this effect is based primarily on numerical models (e.g., Sarmiento and Le Quéré 1996) and has not yet been confirmed by direct observation. In subtropical and equatorial waters, however, future warming may cause the opposite effect. Increased stratification of the water column may lead to a reduced supply of either micro- or macronutrients, a shift to N-fixing organisms, and even lower carbon export than occurs today (Falkowski et al.1998). Some evidence implies that such changes are now occurring in the Northern Hemisphere (Karl et al.1997, McGowan et al. 1998). The potential contributions of such changes to the ocean carbon sink are not yet understood. Hypotheses that link warming-induced changes to upper-ocean stratification (and nutrient flux) and changes to marine ecosystem structure and carbon export are testable using long time-series observations. They may also be tested by focused process studies on ecosystem responses to interannual variability (e.g., during warm versus cold years) and other "natural" experiments.**

**Current understanding of marine ecology and the ability to predict the oceanic response to climate change are extremely rudimentary. It will take at least a decade of research, including long time-series data taken at a number of stations, to significantly improve understanding of the potential responses of oceanic communities to climate change.**

**Continuing to identify the main hypotheses and goals for the CCSP as in Chapter 2, we can then state another fundamental hypothesis for carbon cycle research:**

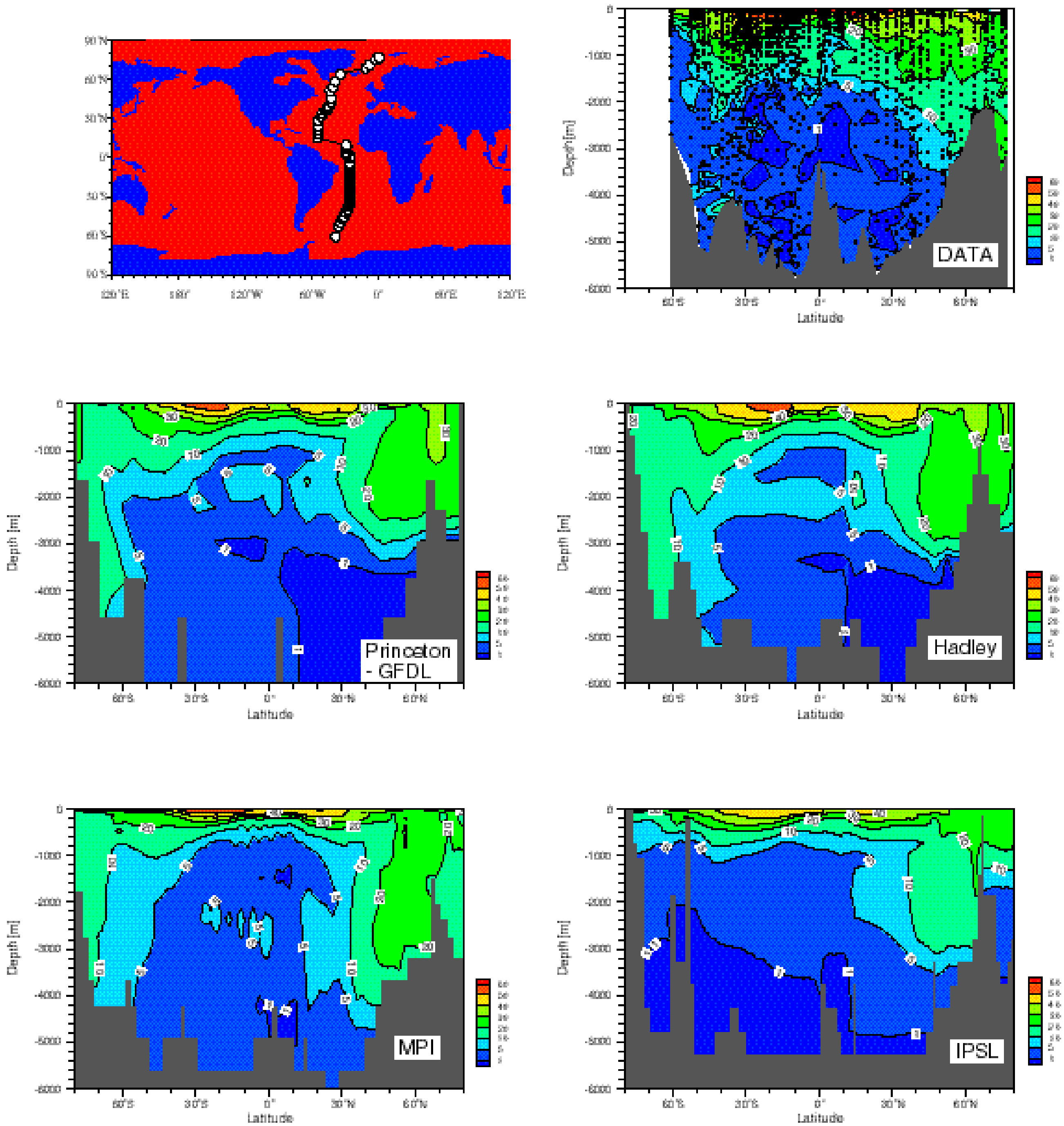
> Hypothesis 2: The oceanic inventory of anthropogenic $CO_2$ will continue to increase in response to rising atmospheric $CO_2$ concentrations, but the rate of increase will be modulated by changes in ocean circulation, biology, and chemistry.

**This hypothesis of an increasing long-term ocean carbon inventory (or "the Increasing Ocean Inventory hypothesis") provides a critical focus for concerns about the future long-term effectiveness of $CO_2$ sinks. One value of a hypothesis concerning future $CO_2$ sinks is that it challenges us to anticipate when and how it can be tested. The estimation of oceanic $CO_2$ uptake has been a primary objective of chemical oceanographic programs for more than two decades (GEOSECS, TTO, SAVE, WOCE, JGOFS[1]). Using a variety of direct and tracer measurements, these programs have considerably improved the ability to model the ocean $CO_2$ sink. The recent advances discussed previously suggest that trends in long-term oceanic $CO_2$ uptake may soon be susceptible to much more direct verification.**

**Like the Northern Land Sink hypothesis, the Increasing Ocean Inventory hypothesis cannot be considered in isolation. For example, it explicitly encompasses the need to understand the effects of variations in oceanic circulation, biology, and chemistry. Such variations have been hypothesized to account for the seasonal and interannual variability in oceanic $CO_2$ exchange associated with the phasing of the El Niño–Southern Oscillation and North Atlantic Oscillation (NAO). Because ENSO and the NAO are also implicated in short-term atmospheric $CO_2$ variations, they must be considered in the use of atmospheric transport inverse models to constrain the Northern Land Sink. Constraints on the spatial distribution of air-sea fluxes are critical to determining the spatial distribution of terrestrial fluxes. Determining the North American or Eurasian fluxes with confidence requires knowing the North Pacific and North Atlantic fluxes. Thus, the Northern Land Sink and Increasing Ocean Inventory hypotheses are directly related and closely linked in a variety of important ways.**

**The Northern Land Sink and Increasing Ocean Inventory hypotheses represent a wide array of perspectives that are inherent in carbon-cycle research: not only terrestrial and marine, but also short-term and long-term,**

**[1] Geochemical Ocean Sections program (GEOSECS); Transient Tracers in the Ocean (TTO); South Atlantic Ventilation Experiment (SAVE); World Ocean Circulation Experiment (WOCE); Joint Global Ocean Flux Study (JGOFS).**




***Data-based and model estimates of uptake of carbon (mmol/kg) released to the atmosphere by human activities, or "anthropogenic carbon," by the Western Atlantic Ocean along a transect illustrated in top left panel. Most of the anthropogenic carbon in the oceans is found in the upper 1 to 2 kilometers except in regions of deep water formation, such as the North and, to a lesser extent, South Atlantic. The ocean has a large capacity to dissolve anthropogenic carbon, but it takes many centuries to millenia for this capacity to be realized. Predicting the future uptake of anthropogenic carbon by the oceans thus requires models of ocean circulation such as those shwn in the bottom four panels of the figure. These models are able to reproduce the general features of the observed anthropogenic carbon distribution, such as the shallower penetration in the low latitudes, and deeper penetration in higher latitudes. However, there are also many differences among the models, and between the models and the observations. For example, all of the models fail to simulate a sufficiently deep penetration between about 30°N and 50°N, and three of them simulate too much penetration in the South Atlantic.***
***This figure was constructed by the Ocean Carbon-Cycle Intercomparison Project team (OCMIP) using a variety of data and model sources including: Orr et al. in preparation, Gruber (1998), Sarmiento et al. (1995), Toggweiler et al. (1989), Taylor (1995), Maier-Reimer (1993), Madec and Imbard (1996), and Aumont et al. (1998).***

regional and global, spatial and temporal, diagnostic and prognostic. They illustrate the extent of integration that is necessary in a framework of evolving hypotheses concerning the global carbon cycle.

To summarize, predicting the future role of oceanic and terrestrial biospheres in determining atmospheric $CO_2$ needs to consider the feedback among climate change and terrestrial and marine biogeochemical processes. Climate change will affect the terrestrial biosphere and ocean; and changes in the terrestrial biosphere and ocean will affect atmospheric $CO_2$. Capturing these mechanisms will require more highly developed models of the terrestrial and oceanic biospheres, ocean mixing and circulation, and their response to warming. A major near-term goal of the CCSP is therefore the following:

Goal 4: Improve projections of future atmospheric $CO_2$ concentrations through a combination of manipulative experiments and model development such that appropriate biophysical and ecological mechanisms and carbon cycle–climate feedbacks are incorporated in global climate and carbon cycle models.

## Management Strategies

The goal of carbon management strategies is to abate the increase of anthropogenic carbon concentrations in the atmosphere. Two approaches for accomplishing this goal are measures to reduce carbon emissions and measures to increase the uptake of carbon by oceanic and terrestrial biosphere sinks. There are no fundamental physical or chemical barriers to using the energy potentially available in fuels much more effectively to bring down the rate of emissions. Relying on low or non-$CO_2$ emitting energy sources is another way of reducing atmospheric $CO_2$ concentrations in the long term. However, in the interim, it is also necessary to consider the option of managing carbon uptake by the oceanic and terrestrial reservoirs.

Exchange with the large geological reservoirs of carbon, such as limestone, is slow. The carbon added to the atmosphere will stay confined to the three "mobile" reservoirs mentioned earlier (i.e., atmosphere, terrestrial biosphere, and ocean) for hundreds of thousands of years. In essence, the burning of coal, oil, and natural gas represents an artificial transfer of carbon from the geological reservoirs to the mobile reservoirs.

The ultimate long-term sink for carbon of the three mobile reservoirs is the ocean. Model calculations show that, on a time scale of 1,000 to 10,000 years, the ocean will absorb about 85 percent of the anthropogenic carbon that has been added to the combined atmosphere-ocean since the beginning of the industrial revolution (e.g., Maier-Reimer and Hasselmann 1987, Sarmiento et al. 1992). The fraction that can dissolve in the ocean decreases as the total amount added to the atmosphere increases. An additional 5 to 10 percent of the combined inventory will be absorbed by the reaction of $CO_2$ with $CaCO_3$ in sediments on a time scale of 10,000 to 100,000 years (e.g., Archer et al. 1997). One way of managing atmospheric $CO_2$ is to accelerate the uptake of carbon by the ocean by pumping it into the slowly ventilated deep waters. These calculations assume that surface ocean temperature, salinity, and alkalinity remain constant, and that the marine cycle of $CO_2$ fixation and sedimentation of organic matter and carbonate skeletons (the "biological pump") does not modify the oceanic carbon distribution significantly.

In the terrestrial biosphere reservoir, photosynthesis removes $CO_2$ from the atmosphere, but much of the carbon is removed only temporarily (IGBP Terrestrial Carbon Working Group 1998). Approximately 50 percent of the initial uptake of carbon from photosynthesis is lost through plant respiration. Again, the carbon remaining after respiration is net primary production (NPP). Part of NPP is lost as litter and enters the soil, where it decomposes, releasing carbon to the atmosphere. On an annual basis, carbon remaining after decomposition is net ecosystem production (NEP). Further carbon losses occur by such processes as fire, insect consumption, and harvest. These losses yield net biome production (NBP), the critical carbon quantity in considering long-term carbon storage. The IGBP Terrestrial Carbon Working Group (1998) argues that belowground components of ecosystems are especially important because belowground carbon generally has slower turnover rates than aboveground carbon. Slower turnover implies that carbon storage can be maintained over longer periods.

An important outcome of better information on land use change (Goal 3 for the CCSP, as outlined in Chapter 2) will be a stronger scientific basis to analyze strategies for managing global carbon fluxes in compliance with international treaties aimed at increasing terrestrial carbon sequestration. We need to know which management strategies for terrestrial biological processes are cost-effective in forests, grasslands, and croplands. Terrestrial ecosystems are partially constrained by the legacy of land use practices in the past. Land use practices are discontinuous in time and space. Hence, in the case of forests, different stands in the same region will rarely be of the same age class and species composition. They will sequester carbon at different rates and in different amounts in response to a given change in management (e.g., changes in harvest rate or predation control) or climate. Delineating these effects will require close coupling between observed land use patterns and trends and corresponding estimates of carbon flux densities, to create

**spatially explicit gradients of carbon flux at regional scales. This effort will require combining satellite and ground-based observation of land use patterns and trends, flux measurements,and process-based modeling. Together, information from all these sources will allow the scientific assessment of management scenarios to increase sequestration of carbon on the land.**

**The scientific evaluation of management options requires the direct involvement of social scientists in constructing land use histories. Thus,there is a permeable boundary between this science plan and the relevant social sciences. Careful assessments are needed of the social and economic costs and benefits of proposed carbon sequestration policies. One critical element will be the development of credible land use scenarios for the future.**

**Another important component of carbon management strategies will be the ability to verify commitments. Other sections of this report discuss the estimation of oceanic and terrestrial sinks. An important additional issue is the estimation of fossil fuel emissions. If the global estimate of fossil fuel emissions based on economic accounting methods is off by 10 percent,that would represent an error of 0.65 Gt C/yr—which is more than the reductions envisioned in the Kyoto Protocol. This error is quite large when trying to balance the global carbon budget with oceanic and terrestrial sources and sinks. The financial and economic stakes in correct carbon accounting are of great importance for any country in a world where emissions permits can be traded. Some measurement strategy is needed,independent from statistical and accounting methods,to determine the magnitude of fossil fuel $CO_2$ emissions on regional and national scales. The only nearly unequivocal (characteristic and stable) tracer for fossil fuel $CO_2$ in the atmosphere is its complete lack of $^{14}C$ isotopes.**

**These considerations lead to another major near-term goal of the CCSP:**

Goal 5: Develop a scientific basis to evaluate potential management strategies for enhancing carbon sequestration in the environment and for capture/disposal strategies.