NACP Committee of the

U.S. Carbon Cycle Science Steering Group

Steven C. Wofsy and Robert C. Harriss, Co-Chairs

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The North American Carbon Program (NACP)

A Report of the

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A plan for carbon cycle research focused on measuring and understanding sources and sinks of CO_2, CH_4, and CO in North America and adjacent oceans. The plan outlines how to implement a principal recommendation of the U.S. Carbon Cycle Science Plan (1999). It was developed as a component of the U.S. Interagency Carbon Cycle Science Program and as a contribution to U.S. climate change research planning.

Prepared at the Request of the Agencies of the

U.S. Global Change Research Program

2002

About the North American Carbon Program Plan

It is currently very difficult to develop policies for global climate change because of unresolved scientific uncertainties, especially about the sources and sinks of the two most important greenhouse gases, carbon dioxide and methane. These gases are the major causes of changes in atmospheric composition that may force climate change. Policy and decision makers would like to know with a high level of confidence what would be the likely outcomes of actions affecting the carbon cycle, and these gases in particular. They want to avoid surprises and unintended consequences. This is not yet possible in considering climate change.

The North American Carbon Program (NACP) will provide scientific information critical to reducing uncertainties, helping to pave the way for effective, efficient policies. The program focuses on North America and its adjacent oceans for the following reasons:

- The large uncertainty surrounding the magnitude of North America's contribution to an overall Northern Hemisphere carbon sink.
- It is a region of significant fossil fuel emissions.
- Partial infrastructure is in place to begin characterizing the mechanisms controlling North American sources and sinks.
- The continental scale is the smallest scale of integration that will allow the information to be analyzed in a global context.

The knowledge that will be gained in the NACP program will provide a strong scientific underpinning to inform future policy decisions involving the carbon cycle, such as managing carbon sources and sinks by efficient and effective options that reduce emissions or enhance carbon sinks. The NACP addresses infrastructure and scientific and policy issues by focusing on a number of goals:

- Maintaining and enhancing U.S. leadership in climate change science and technology development
- Strengthening basic and applied research on short and long-range products useful for technology and policy development
- Enhancing coordination across federal agencies, and among the federal government, universities, and the private sector
- Providing public-private partnership opportunities
- Promoting international cooperation
- Developing improved technologies for measuring and monitoring gross and net greenhouse gas emissions
- Determining the nature and causes of natural variations in the carbon cycle, including feedbacks, thus providing climate change forecasting capabilities
- Providing the scientific understanding to account for, predict, and manage the carbon cycle for North America.

The program plan is offered as a guide to responsible federal agencies for implementing priority carbon cycle research, in which close coordination among agencies, and between the scientific community and the agencies, is essential.

It was prepared by the undersigned at the request of the Carbon Cycle Science Steering Group. A draft of the plan was circulated to the scientific community and interested federal agencies in August 2001, and extensively debated and revised at the Workshop on the North American Carbon Program, in Boulder, Colorado, 5–7 September 2001, prior to formal presentation to the Carbon Cycle Interagency Working Group. The members of these groups and their email addresses are listed below.

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Motivation for the North American Carbon Program (NACP)

In a recent report, the National Academy of Sciences (NAS, 2001) concluded that "progress in reducing the large uncertainties in projections of future climate will require addressing a number of fundamental scientific questions relating to the buildup of greenhouse gases in the atmosphere and the behavior of the climate system." The NAS report identified research on sources and sinks of carbon dioxide (CO_2) and other greenhouse gases as critical to reducing this uncertainty:

- "How land contributes, by location and processes, to exchanges of carbon with the atmosphere is still highly uncertain" (p. 11).
- "How much of the carbon from future use of fossil fuels will be seen as increases in carbon dioxide in the atmosphere will depend on what fractions are taken up by land and by the oceans. The exchanges with land occur on various time scales, out to centuries for soil decomposition in high latitudes, and they are sensitive to climate change. Their projection into the future is highly problematic" (p. 18).

The North American Carbon Program presented in this report describes related issues and a coordinated research effort to address them, focusing on North America and adjacent ocean basins. The plan outlines how to implement a principal recommendation of the U.S. Carbon Cycle Science Plan (Sarmiento and Wofsy, 1999). It is developed as a component of the U.S. Interagency Carbon Cycle Science Progrm and as a contribution to US climate change research planning.

Atmospheric CO_2 has increased dramatically since the Industrial Revolution, principally owing to the combustion of fossil fuels, and has affected climate and plant metabolism worldwide. But less than half of the CO_2 emitted has remained in the atmosphere. The remaining part has been taken up and stored as organic matter in vegetation, soils, and river basins on land, or as organic sediments or dissolved bicarbonate in the sea. Roughly 40% of fossil fuel input was removed in these ways in the 1980s, increasing to 50% in the 1990s (Battle et al., 2000). Measurements suggest that much of the non-atmospheric global uptake of CO_2 may be in North America, although the conclusion is controversial because the data are grossly inadequate. Understanding why, and where, CO_2 uptake has occurred is critical for knowing how the Earth's atmosphere and climate will evolve in the future, and what can be done about it.

Atmospheric methane (CH_4) is second to CO_2 as an anthropogenic greenhouse gas. Concentrations of CH_4 have nearly tripled since 1700, but the rate of change has varied over time. Basic questions remain unanswered about why global changes in atmospheric CH_4 have occurred.

Carbon monoxide (CO) is a key air pollutant and can be used as a tracer to distinguish combustion from biogenic sources of CO_2.

Carbon stocks, the aggregate sums of carbon stored on land (organic matter in vegetation and soils) and in the oceans (e.g., organic or inorganic carbon in the water column or sediments), include economic resources such as timber. Changes in stocks can also either moderate or amplify atmospheric CO_2 increases. Any possible efforts to manage carbon through sequestration of atmospheric CO_2 in terrestrial or marine systems require observations and models to verify changes in stocks. International agreements to manage carbon also need reliable data on changes in carbon stocks, but current inventories lack sufficient scientific underpinnings for accurate, verifiable determinations.

The NACP focuses on the carbon-containing gases CO_2, CH_4, and CO, and on carbon stocks in North America and adjacent ocean basins. The program responds to the NAS report by seeking scientific understanding of sources and sinks for CO_2, CH_4, and CO, and of changes in carbon stocks needed to meet societal concerns and to provide tools to policy makers. The NACP addresses several basic questions:

- What is the carbon balance of North America and adjacent ocean basins, and how is the balance changing over time? What are the sources and sinks, and the geographic patterns of carbon fluxes?
- What factors control the sources and sinks, and how do they change with time?
- Are there potential "surprises," where sources could increase or sinks disappear?
- How can we enhance and manage long-lived carbon sinks to sequester carbon?

The NACP will ultimately enable sustainable carbon management by developing proven scientific tools to diagnose past and current sources and sinks of greenhouse gases, and to predict future contributions from North America and adjacent ocean basins. The program will inform future decisions on policies to reduce net emissions of CO_2 and CH_4, and to enhance sequestration of carbon through land management or by other means.

The program is optimally designed to advance science for other critical problems: (1) the large-scale emissions, transformations, and long-range transport of air pollutants; (2) changes in species composition, health, and productivity, and the vulnerability to fire and drought of forests, croplands, and wild lands; and (3) forecasts of weather and climate.

Goals of the NACP

The NACP has three overarching goals:

- Develop quantitative scientific knowledge, robust observations, and models to determine the emissions and uptake of CO_2, CH_4, and CO, the changes in carbon stocks, and the factors regulating these processes for North America and adjacent ocean basins.
- Develop the scientific basis to implement full carbon accounting on regional and continental scales. This is the knowledge base needed to design monitoring programs for natural and managed CO_2 sinks and emissions of CH_4.
- Support long-term quantitative measurements of sources and sinks of atmospheric CO_2 and CH_4, and develop forecasts for future trends.

Major Program Elements of the NACP

Major NACP program elements consist of atmospheric measurements, which show how land and oceanic systems influence atmospheric CO_2 concentrations, and which provide crucial information for inferring carbon sources and sinks; models that assimilate and synthesize observational data; and measurements of carbon inventories and fluxes on land and in adjacent ocean basins, which allow assessing those mechanisms that ultimately determine atmospheric concentrations.

Atmospheric Measurements and Field Programs

Long-Term Atmospheric Measurements of the Carbon Budget. Ground-based, aircraft, and satellite measurement networks will provide spatially and temporally resolved, three-dimensional atmospheric data for the major carbon gases CO_2 CH_4, and CO, to enable reliable estimates for U.S./North American sources and sinks of these gases. These observations are required to obtain regional and continental sources and sinks for atmospheric CO_2, CH_4, and CO.

Intensive Field Programs. Large-scale airborne and field campaigns will provide data sets to evaluate and improve the design of atmospheric and surface measurement networks, to develop and test models that interpret observations, and to provide atmospheric "snapshots" to constrain fluxes. This effort will provide continual feedback on uncertainties in modeling and assessment tools for carbon accounting.

Inventories and Land and Ocean Surface Processes and Fluxes

Terrestrial Measurements and Modeling: Understanding the Land Biosphere. The NACP will combine enhanced carbon inventories, remote sensing, and models to provide a complete carbon accounting for the land sector, and comprehensive analysis of the mechanisms driving the fluxes. Full carbon accounting and attribution among causes will address fluxes of CO_2 and CH_4 in all major ecosystems, including forests, wetlands, and agricultural, urban, and suburban lands. New emphasis on carbon accounting, on lands (peatlands, scrub land, suburban landscapes) and carbon pools (roots, coarse woody debris, shrubs) not currently inventoried, and on scaling with remote sensing and models will all greatly improve the carbon budget for North America.

A hierarchical approach will support a multi-scale interpretation, with intensive studies providing access to details and mechanisms that are extended using remote sensing, extensive inventories, and mechanistic models. This multi-scale approach to land data will join the atmospheric and ocean studies as components in a unified analysis framework. Constraints from the atmosphere and oceans will increase the sophistication and accuracy of the estimates based on land data.

Marine Measurements and Modeling: Understanding Physical and Biological Processes in Ocean Basins Adjacent to North America. High-resolution measurements of air-sea fluxes of CO_2, and process studies in coastal waters and adjacent ocean basins will define contributions of the ocean margins and adjacent ocean basins to the North American carbon budget. Large-scale ocean basin studies will help place North America in a global context and enable inverse model estimates of the North American carbon cycle. Establishing the oceanic boundary conditions for the continent is essential for accurate carbon accounting.

Integrating Models and Model-Data Assimilation

NACP data sets will be quantitatively and qualitatively different from current data. We will know the atmospheric concentrations of CO_2, CH_4, and CO over the entire continent and adjacent waters at frequent intervals, requiring development of advanced database management, diagnostic models, and data assimilation. The flow of information and the integration to obtain regional carbon accounting are shown in Figure 1.

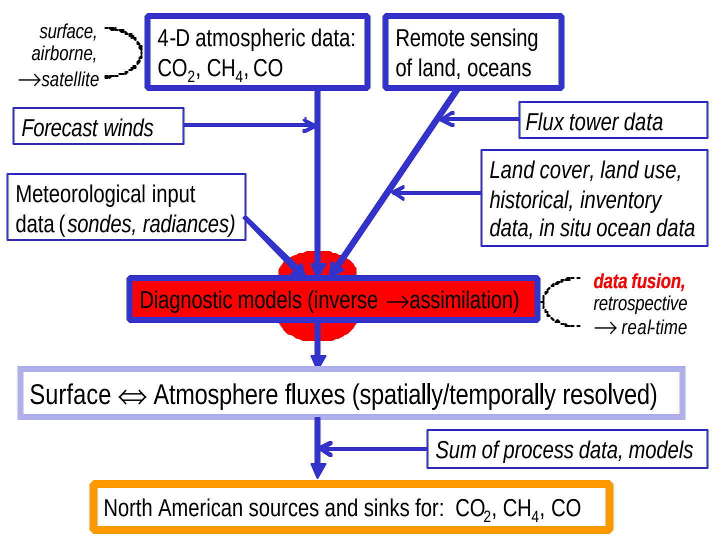

Figure 1. Data flow and integration in the NACP.

Figure 1 illustrates data flow and integration in the NACP. Complexity and level of synthesis increase down the figure. Valuable data products are delivered at each level. Note the central role played by the model-data fusion systems that combine observations from diverse sources, using data-driven models and advanced data assimilation and optimization methods.

A critical step will be to develop new classes of models to determine sources and sinks of CO_2, CH_4, CO, and other gases. The new diagnostic systems will build on, and complement, more conventional top-down ("inverse models") and bottom-up ("ecosystem models") analyses applied in the new, data-rich environment. Data-driven models of carbon dynamics in vegetation and soils will be combined with high-resolution meteorological information, surface flux data, and atmospheric concentrations to derive fluxes. Using advanced techniques, a quantitative representation of the state of the atmosphere and of the carbon cycle will be obtained consistent with atmospheric, oceanic, and land data in real time. Through the NACP, these new models will provide potent diagnostic and predictive capability for surface-atmosphere fluxes of CO_2, CO, and CH_4.

Implementing the NACP

The NACP introduces many new elements into climate research, elements that must be tested and refined as the program proceeds. Thus, new long-term measurements, models, and analyses will be implemented in phases, closely coordinated from the start, with major initiatives in four key areas: (1) atmospheric measurements; (2) measurements, process studies, and modeling of land ecosystems (plants and soils) and adjacent ocean basins; (3) models that integrate atmospheric, land, and ocean data; and (4) regular state-of-the-art assessments of carbon cycle science and carbon inventories for North America. The new science to diagnose exchange fluxes between the Earth's surface and the atmosphere is coupled from the start with communication of results to the public.

Implementation of the NACP is envisioned in the form of three phases:

Phase 1. In the initiation phase (2002 – 2005), the program will include development of new instrumentation and initial model development for model-data fusion. Current agency programs will be realigned and refocused to strengthen existing measurement networks and inventories. Data sets for land disturbance history will be developed from satellite (e.g., LandSat) and land use inventory archives. Workshops will assess current uncertainties in CO_2 and CH_4 emission and sink inventories. Costs in the near term are modest as summarized immediately below (under "Highest Priority Enabling Developments"). Intensive field campaigns will test and refine the conceptual framework, starting in 2004, with a joint NACP-tropospheric chemistry study, the

Intercontinental Transport Experiment—North America (INTEX).

Phase 2. During the testing and implementation phase (2005–2008), the program will undertake stepwise installation of the new observational network, including atmospheric, terrestrial, and marine elements, and further develop model-data fusion systems. New field measurements and procedures to integrate data from the NACP elements will be tested and refined by intensive field experiments. Space-borne data for biomass are expected to enhance regional terrestrial and marine carbon accounting capabilities. *Phase 2 costs are estimated to be $50–$100 million per year above fiscal year 2002 expenditures.*

Phase 3. In the operational phase (2008–), the networks and model-data fusion system will deliver reliable estimates of net sources and sinks for CO_2, CO, and CH_4, and of changes in carbon stocks over North America, along with a full suite of observations and associated analytical enhancements for a range of other science and operational objectives. Spacecraft that accurately measure atmospheric concentrations of CO_2 and CH_4 are envisioned for this time. *Costs for this operational phase of the program are estimated to be $50–$100 million per year above fiscal year 2005 expenditures.*

Highest Priority Enabling Developments for the NACP

The following are critical needs in the near term to enable initiation and development of the NACP, and are recommended for immediate action. Estimated additional costs represent the latter part of Phase 1 (i.e., entry to Phase 2).

1. Develop in situ sensors and sampling protocols for aircraft, ocean, tower, and soil and vegetation flux measurements of CO_2, CO, and CH_4. These should be robust, accurate, and operable by minimally trained personnel. The instruments represent near-term deliverables of the program. Cost estimates broken down by area are $1 million over two years for atmospheric CO_2, $1 million over two years for atmospheric CO and CH_4, $1–$2 million per year for two years for ocean CO_2 buoy development, $1 million per year for two years for soil fluxes, and $2 million per year starting in two years for initial testing and deployments. *The total cost estimate is thus approximately $5–$7 million per year.*

2. Perform model studies of network design and model-data fusion. This work requires a summer study institute, then sustained efforts to develop data assimilation/fusion systems by intensive evaluation of models against new data, such as flux and isotopic measurements. Components envisioned are a science team of about five groups outside operational centers ($1.5 million/year) and funding for NASA's Data Assimilation Office (DAO), GFDL, and/or NWS's National Centers for Environmental Prediction (NCEP) (with 10-20 full-time equivalents, $1.5–$3 million/year), plus computer hardware ($1–$2 million).

A 20-year reanalysis of global meteorology, with a 10-km nested grid over North America, should be initiated in Phase 1 at one or more operational centers. This activity will deliver a critical product, with data tailored for mass budget analyses, for hindcasting and for refining network concepts using preexisting data. The estimated additional cost is $1–$2 million/year for one to two years to do this rapidly and enable the studies noted. The reanalysis is a near-term deliverable. *The total cost estimate is $5–$8 million/year.*

3. Optimize national inventories for carbon accounting. Strategic enhancements are needed in current network designs for complete carbon accounting. Historical data on land cover, management, and disturbance need to be compiled and made available, and gaps must be filled by statistical estimation ($1–$2 million/year). Benefits will include more consistent and comprehensive historical data on land ecosystems, past human impacts, and natural disturbances. Gaps in geographic and biome coverage should be filled, especially for rangelands, mountainous areas, and developed lands. The USDA's Forest Inventory Analysis and National Resources Inventory is a high priority for a strategic enhancement. The cost of additional sampling is $16–$32 million per year, but this sampling has many further benefits and should not be attributed entirely to the NACP. *Total cost estimates attributable to the NACP, $10 million per year.*

4. Strengthen current observation networks.

(a) Fill gaps and weaknesses in the current long-term measurements of greenhouse gases in the United States. The NOAA-CMDL greenhouse gas programs require sustained long-term ("baseline") funding at $2–$4 million per year above current levels. These steps are extremely urgent to allow an expanded NACP program over the following five years, or even to maintain the status quo. Time-series ocean moorings are needed for atmospheric CO_2 and marine pCO_2 ($2 million/year). Better tracking of atmospheric trends are a near-term deliverable. *Total cost estimate is $4–$8 million per year.*

(b) Begin the transformation of the AmeriFlux network into an integrated, near–real time network, and add representative long-term sites. Each new site will cost $300,000 plus $400,000/year to run and analyze data. The core AmeriFlux program needs strengthening, with enhanced quality controls, oversight, and improved information management systems. New sites in critical undersampled ecosystems, and projects to understand fluxes in complex terrain are needed. Costs for three to five new sites per year represent a ramp-up of $1 million per year for three years. Data on climate and pollution effects on ecosystems and agriculture are short-term deliverables. *Total cost estimate is $8–$10 million per year for these items.*

5. Improve databases for fossil fuel use and land use/land cover. A *State of the Carbon Cycle for North America* report will be prepared that addresses current knowledge and new advances in understanding of all components of the natural and managed carbon cycle. This assessment will be updated as significant new findings are produced. Initially, the focus will be on establishing a consistent inventory of sources and sinks of CO_2 and CH_4 with associated uncertainties for each source and sink category. Methods to better integrate historical land use and inventory information with contemporary satellite estimates of land cover and use will be a crucial aspect of improving the quality of source and sink estimates. The improved databases and report will provide regularly updated information relevant to informing policy. *Estimated costs are $1–$2 million per year.*

6. Develop remote-sensing technology. Better remote-sensing technology is needed for atmospheric CO_2, CH_4 and CO, and for above-ground biomass and soil moisture. Satellite data will be the key to long-term, accurate NACP data in the 5- to 10-year time frame. Near-term efforts should focus on airborne simulators of future spacecraft instruments, and on critical assessment of early products for atmospheric CO_2 from existing satellites. The airborne simulators will be used to measure in situ profiles/columns of the gases. Airborne simulators are also essential to technology development for biomass and soil moisture satellite sensors, and will be extremely useful for intensive studies before spacecraft are deployed. Technology development is the near-term deliverable. *Estimated new near-term costs for concept and technology development are $20–$25 million per year.*

Total costs for Phase 1 ramp-up over five years from current expenditures are estimated at approximately $45–70 million above current levels. Much could be accomplished in the first and second years by focusing and coordinating current agency budgets.

Integration

An unprecedented level of integration among NACP elements is needed to resolve and attribute mechanisms for sources and sinks of CO_2 and other greenhouse gases for North America. Previous carbon cycle research largely focused on studies of single components, such as the atmosphere or ocean, or employed small-scale process studies. But carbon is exchanged continuously through the atmosphere, land biosphere, soils, and oceans, and simultaneous study of these systems is required to obtain a coherent view of where and how carbon is stored in the North American region. The temporal and spatial scales of the program must be appropriately large for addressing climatic issues, and data and models from all components must be brought together to develop information on global carbon balances.

Integrating NACP elements is also essential to obtain quantitative understanding of the mechanisms regulating uptake of carbon. Mechanistic information on carbon uptake is gained at a local level, through process studies and inventories. But results must be scaled up and compared to information gained at regional and continental scales to determine the importance of mechanisms regulating carbon balances, and to project future operation or potential for management.

The NACP therefore emphasizes coordination and integration. A major element for this is provided by innovative new assimilation and data fusion systems that bring together diverse data and models, linking information at various scales to provide a consistent North American carbon balance. This coordination of science activities requires similar coordination among agencies involved in implementation, including inter-agency scientific and management committees, to ensure delivery on NACP goals.

Management

The NACP requires extraordinary management arrangements because of the need for integration. The program's elements will be implemented by several federal agencies, which should obtain scientific guidance from a unified science advisory committee to ensure that program elements are working together as necessary. There is already notable coordination among agencies at the level of scientific research programs, through the Carbon Cycle Interagency Working Group. The CCIWG commissioned the current plan to help implement a major element recommended in the Carbon Cycle Science Plan (Sarmiento and Wofsy, 1999). The NACP will also require a comparable degree of integration and coordination at higher, policy-making levels of the responsible federal agencies.

Synergy with Other Scientific Problems of Social Interest

Atmospheric Chemistry. Carbon gases (CO_2, CH_4, and CO) are intimately associated with the principal sources of air pollution. The NACP will provide spatially and temporally resolved surface-atmosphere fluxes and long-range transport fluxes, helping to determine how much pollution is transported across the oceans to and from North America, and how redistribution of pollution occurs within North America. The framework of observations and data assimilation can be readily adapted to provide regional and continental sources and to define import and export fluxes of pollutants.

Resource Management and Ecological Sciences. The carbon budget of a region is an emergent property defining the health and productivity of ecosystems. NACP data will define processes related to carbon sequestration by major crops, fuel accumulation on fire-prone lands, and responses of major land and ocean ecosystems to environmental stresses (e.g., ENSO).

Weather Forecasting and Climate Modeling. Tracer distributions from the NACP will give direct measures of transport processes in the planetary boundary layer, long a bane of forecast models. Data for CO_2 concentrations and fluxes directly benefit temperature retrievals. Climate feedback involving CO_2 and CH_4, the principal focus of the NACP, are major issues for climate prediction.

Formulation of Economic Methods for Carbon Management. The carbon accounting information produced by the NACP will support the development of robust, market-based tools and methods for national and international programs on carbon management.

Summary of Overall NACP Deliverables

- Measurements of sources and sinks for CO_2, CH_4, and CO for North America and adjacent ocean basins, at scales from continental (5,000 km) to local (10 km), with seasonal resolution.
- Attribution of sources and sinks to contributing mechanisms, including climate change, changes in atmospheric CO_2, nutrients, pollutants, and land use history.
- Documentation of North America's contribution to the Northern Hemisphere carbon budget, placed in the global context.
- Optimized sampling networks (both ground-based and remote) to determine past, current, and future sources and sinks of CO_2, CH_4, CO, and major pollutants.
- Data assimilation models to compute carbon balances.
- *State of the Carbon Cycle for North America and Adjacent Ocean Basins*, a periodic report communicating results to the public.
- Data and observations to enable major advances in atmospheric chemistry, such as better determination of sources and transformations of pollutants; in resource management, as through improved knowledge of ecosystem function and response to global changes; and in weather forecasting and climate models, through real-time tracer concentration and flux data, and coupled models with improved representations of atmosphere-biosphere coupling, surface energy, and mass fluxes.

Near-Term Deliverables of the NACP (2004-2007)

- The first comprehensive North American *State of the Carbon Cycle* report, based on NACP results, synthesizing historical estimates and current measurements of carbon sources and sinks (2004).
- Comprehensive inventories and databases on fossil fuel use, vegetation, soils, and land use and management in North America (2005).

- Improved networks, sampling protocols, and data to track global and regional trends in atmospheric CO_2, CO, CH_4, ozone-depleting gases, and air pollutants, and carbon stocks (2005).
- Improved data on the responses of terrestrial and coastal marine ecosystems (both managed and natural) to climate variations and pollution (2003-2005).
- A new generation of prototype in situ and remote-sensing instruments essential for monitoring the status and trends of carbon sources and sinks at regional, national, and continental scales (2005).
- High-resolution analysis of global weather from 1980 to the present. Carbon accounting models will combine these data with inventories of fossil fuel use, vegetation, soils, land cover and land management to significantly reduce uncertainties in the recent status and trends of North American sources and sinks of carbon (2006).
- A second comprehensive North American *State of the Carbon Cycle* report, characterizing uncertainties in both historical estimates and current measurements on carbon sources and sinks. This assessment will be a major resource for the design of market-based methods for carbon management (e.g., carbon trading), and for policy formulation (2007).

Chapter 1: Introduction

Introduction: Motivation, Major Goals and Program Objectives

The North American Carbon Program described in this document represents a major expansion of U.S. efforts to address gaps in scientific knowledge of climate change. The central goal is to provide the scientific information needed to inform policies designed to reduce contributions by the United States and neighboring countries to atmospheric carbon dioxide (CO_2) and methane (CH_4). The program will provide scientific data and analysis to determine the fate of CO_2 emitted to the atmosphere by combustion of fossil fuels. It is also aimed at comprehensive understanding of the rates and mechanisms controlling carbon uptake and release from soils and vegetation in North America and the adjacent Atlantic and Pacific Oceans. Additionally, the program will develop reliable quantitative knowledge of the sources and underlying processes that release other important gases, including carbon monoxide (CO), to the atmosphere.

The broad goal is to reduce uncertainties about the carbon cycle component of the climate system, and to develop scientific and technical tools to forecast future increases in concentrations of atmospheric CO_2 and CH_4, the most important greenhouse gases. The intent is to provide the scientific information needed to design effective and economical policies for the United States and neighboring countries to manage carbon sources and sinks.

The program's focus on North America is designed to deliver the detailed process-level understanding of CO_2, CH_4, and CO sources and sinks that will be required to design carbon management strategies for the United States, Canada, and Mexico. North America is a major part of the global carbon cycle, and its diverse climate and ecological zones provide analogues for many parts of the world. Thus, the NACP will help build the foundations for analysis of the carbon cycle worldwide.

The Opportunity

A strong scientific consensus now exists that human emissions of greenhouse gases have important climatic consequences, and that these consequences, as well as the impacts on ecological balances from the direct physiological effects on vegetation, will grow in the future. A primary cause of these changes is the increase in atmospheric CO_2, which is emitted to the atmosphere by burning of fossil fuels, cement production, and changes in land use such as deforestation. Carbon dioxide is inert in air, and thus is not removed by chemical breakdown in the atmosphere. Nevertheless, only about half of the CO_2 released to the atmosphere since the beginning of the industrial revolution remains there. The portion removed has been taken up and stored in the oceans and on land, by processes that we refer to as "sinks." Studies to identify and understand sinks have emerged as critical for assessing long-term changes in atmospheric concentrations in the past, and will dramatically enhance understanding of how the earth's climate will evolve in the future.

Atmospheric CH_4 is second only to CO_2 as an anthropogenic greenhouse gas. A molecule of CH_4 may contribute more than 20 times as much as a molecule of CO_2 to radiative forcing, and CH_4 is also a key species in the chemistry of the atmosphere. Methane was, until recently, the most rapidly increasing greenhouse gas, rising 145% since the beginning of the industrial revolution. After years of near-steady growth averaging about 12 ppbv/yr, growth rates became unsteady in the 1990s, from 15 ppbv/yr (1991, 1998) to 0 ppbv (2000). The long-term increase and currently variable growth rates are not well understood, and we cannot presently predict future increases or decreases with confidence.

The study of the global carbon cycle has the potential for fundamental breakthroughs in the next few years. A number of recent developments bring us to this important threshold.

- Atmospheric measurements and transport models enable increasingly accurate quantification of regional sources and sinks for CO_2 and CH_4.
- High-resolution measurements of carbon isotopes and oxygen are establishing the relative size of carbon sinks on land and in the oceans.
- New satellite sensors provide the foundation for more sophisticated and accurate estimates of land and ocean primary production, as well as changes in land use and land cover.
- An increasingly comprehensive network of local-scale flux experiments is powering a new generation of process studies and interpretations

- Ocean measurements are able to discern human effects on ocean carbon, allowing quantification of exchange between air and sea on decadal time scales.
- Inventories of forest, grassland, and agricultural regions are quantifying regional carbon sources and sinks, and the processes that contribute to them, with higher resolution and accuracy.
- Experimental studies simulating past and future conditions are revealing new details about the mechanisms regulating the exchange of carbon between land vegetation and the atmosphere and between the ocean and the atmosphere.
- A growing interdisciplinary community is documenting past and present patterns of land use and cover change.
- Mathematical models to simulate carbon balance at local, regional, and global scales have the power and reliability to serve as integrators of diverse data streams.

The scientific agenda for crossing this threshold was outlined in the document *A U.S. Carbon Cycle Science Plan* (CCSP) (Sarmiento & Wofsy, 1999), developed by a broad community of scientists responding to a request from federal agencies participating in the U.S. Global Change Research Program. The CCSP addresses two fundamental scientific questions:

- What has happened to the carbon dioxide that has already been emitted by human activities (past anthropogenic CO_2)?
- What will be the future atmospheric CO_2 concentration trajectory resulting from both past and future emissions?

These questions, extended to include CH_4, were articulated into long-term goals:

Goal 1. Quantify and understand the Northern Hemisphere terrestrial carbon sink.

Goal 2. Quantify and understand the uptake of anthropogenic CO_2 in the ocean.

Goal 3. Quantify and understand the global distribution of carbon sources and sinks and their temporal dynamics.

Goal 4. Determine the impacts of past and current disturbance, both natural (e.g., boreal fires) and anthropogenic (e.g., land use) on the carbon budget.

Goal 5. Provide greatly improved projections of future atmospheric concentrations of CO_2 and CH_4.

Goal 6. Develop the scientific basis for societal decisions about management of CO_2, CH_4, and the carbon cycle.

Targeted investments in carbon cycle research can yield large dividends in advancing scientific research, assessment, and decision making, providing a direct response to the recent report from the National Academy of Sciences, *Climate Change Science: An Analysis of Some Key Questions* (NAS, 2001). This report (commissioned by the White House) attached the highest priority to scientific research on the carbon cycle.

The national dialogue on policy issues related to the carbon cycle will demand increasingly better data and predictive capabilities in the coming years. The North American Carbon Plan (NACP) described in this document provides a core element of an overall strategy for supporting that dialogue, providing science at a new level of relevance and credibility for North America and the Northern Hemisphere. The NACP should be viewed as a major component within the broader context of the U.S. Carbon Cycle Science Plan, and complements other planning efforts for the CCSP. For a summary of recommendations regarding global scale atmospheric and oceanic in situ monitoring, see the *U.S. Large Scale CO_2 Observation Plan* (LSCOP) (Bender et al., 2001).

A New Integrative Framework

The NACP is a set of multiagency, integrated research initiatives focused on the United States, Mexico, and Canada, and adjacent oceans, to quantify regionally resolved sources and sinks for CO_2, CH_4, CO, and to understand the underlying processes.

The program will provide comprehensive understanding of uptake and release of these gases. It will separate influences of combustion and biogenic sources, and determine the sensitivity of sources and sinks to environmental conditions (climatic variations, sunlight, temperature, soil moisture), ecological and historical factors, (phenology, vegetation cover, prior land use), and management (in forests, agricultural land, and wild lands). The NACP will assemble the knowledge required to assess future carbon content of the oceans, land, and atmosphere for future scenarios of emissions, and provide a basis for carbon management and carbon trading.

Recent research has led to the development of key techniques and the discovery of critical results about many aspects of the carbon cycle. The NACP envisions bold new steps in scientific integration and communication, building on past progress, to put these techniques and results to work in the interest of the public and decision makers. The new integrative framework will need to incorporate data from a wide range of sensors, locations, and processes and to connect measurements obtained at the "leaf level" with regional and continental scale data. The results of this integration need to be assessed, applied to the broad range of issues affected by the carbon cycle, and communicated to stakeholders in comprehensive scientific reports on the state of the carbon cycle. The specific needs can be described by means of the following three categories:

1. Comprehensive long-term and intensive observations to quantify carbon stocks and fluxes for the atmosphere, plants, soils, and oceans.

Presently, the major limitation on our ability to localize and quantify carbon sources and sinks is the sparseness of most data sets, and lack of integration of different types of data. Because no single set of measurements is definitive, we recommend strengthening the network of atmospheric, ocean, and land measurements, making each more complementary to the others. Specific tasks that contribute to this would include the following:

- Strengthen the nation's network for continental and global atmospheric sampling of CO_2, CH_4, and other greenhouse gases, including additional surface stations plus frequent, long-term, samples from a range of altitudes, using aircraft, tall towers, flux towers, and surface stations.
- Develop the technology for measuring accurate concentrations of atmospheric CO_2 and CH_4 from satellites.
- Deploy aircraft experiments designed to quantify the variability of atmospheric CO_2, CH_4, and CO over a range of spatial and temporal scales, to design efficient, long-term, monitoring strategies.
- Enhance inventories for carbon accounting in North American rangelands, forests, wetlands, and agricultural lands to include the full range of locations, plants, and soils.
- Synthesize data on past and present land use and land cover change.
- Develop monitoring techniques and strategies to measure the efficacy and impacts of carbon management programs.
- Develop instruments, including airborne instrumentation for routine measurements of CO_2, CH_4, and CO, for routine vertical profiling, and shipboard and moored autonomous devices to assess mechanisms controlling ocean CO_2 fluxes.
- Enable sustained observations to track the movement of carbon from the ocean surface to interior.
- Utilize data collected during field studies to develop and improve algorithms for current and proposed satellite sensors that provide information about land and ocean fluxes of CO_2, CH_4, and CO.
- Improve the accounting of emissions of CO_2, CH_4, and CO from human activities, and clarify the links between carbon emissions and economic activity, food security, and quality of life.

2. Process studies to define key mechanisms responsible for carbon exchanges among the atmosphere, oceans, and land.

A comprehensive understanding of the carbon cycle on land and in the oceans will require improved understanding of particular mechanisms and combinations of processes. Process studies are especially critical for isolating effects of individual mechanisms, facilitating their representation in models, and for projecting carbon cycle processes outside the range of current conditions. A number of specific goals warrant increased emphasis:

- Expand and strengthen the nation's network of studies to measure CO_2 and CH_4 exchange between land vegetation/soils and the atmosphere using flux towers (AmeriFlux) and ecological and edaphic measurements, emphasizing the understanding of year-to-year variation
- Quantify carbon storage and release due to land management practices, including those designed to enhance carbon sequestration in biomass and/or soils.
- Perform manipulative experiments to understand the effects of enhanced nutrient availability on carbon uptake in the ocean and of simulated global changes on ecosystem carbon balance on land.

- Conduct field studies to evaluate the effectiveness of deliberate management strategies to sequester carbon in the oceans and on land, as well as the impact of these strategies on natural and human systems.
- Explore the interaction between carbon cycle management, including sources of CH_4 and sources and sinks of CO_2, and social systems, including economic, institutional, and sociological aspects.

3. Quantitative frameworks to integrate the observations and process studies for scientific and decision-making objectives.

Integrating the products of the observations and process studies will require targeted improvements in the models and in the infrastructure that supports integrative work. There are several specific needs:

- Improve the representation of past human actions in carbon cycle models
- Integrate short-term responses to weather and long-term responses to ecosystem development and climate in carbon cycle models
- Strengthen the representation of ocean circulation in the ocean component
- Evaluate and validate the representation of underlying mechanisms, including social and economic processes
- Improve the infrastructure for developing and running integrated models with land, ocean, and atmospheric components
- Develop "nested" models, with the capability to provide information on a wide range of spatial scales, from a few meters to the entire globe
- Assemble sufficient computing resources to run fully coupled models that link a dynamic carbon cycle, including CO_2 and CH_4, to climate, biological processes, land use change, climate, and ocean circulation.

Building a North American Partnership

The NACP aims to quantify and understand land biosphere–atmosphere carbon fluxes, emphasizing processes in North America for the following reasons: (1) there is intrinsic interest in the United States, Canada, and Mexico, with their strong sources of fossil fuel emissions of CO_2, CH_4, and CO; (2) the proposed research methods should be evaluated within a limited area before application to larger regions and eventually the globe; and (3) logistics and technology do not yet allow such an approach on a global scale. The long-range goal of the proposed program is to develop a system that ultimately will contribute to understanding the carbon cycle on a global scale. One of the challenges will be to develop partnerships with Canadian and Mexican researchers, ideally at scientist-to-scientist and agency-to-agency levels. NASA's highly successful Boreal Ecosystem Study (BOREAS, 1993-1999) is a model of productive scientific cooperation with a neighboring country in carbon cycle studies.

Parallel Efforts in Europe, Australia, and Japan

The EU and European nations are sponsoring an ambitious carbon program, including process studies, eddy flux, surface concentration and airborne profiling in Continental Europe and in Russia. A project ("COCO") will assimilate radiances from the NASA AIRS instrument to retrieve global CO_2 concentrations from space. The European Centre has an impressive program to develop high-resolution meteorological models and projects to enable assimilation of atmospheric CO_2 data. Japan supports both flux and free-air measurements of CO_2 at home and in Siberia. Australia has a vigorous program that emphasizes coupled development of observing systems and models. Several European countries as well as Japan are also mounting basin-scale ocean carbon observational campaigns.

The NACP is intended to be a major component of the emerging international framework for carbon studies, eventually leading to integration of these regional programs into global assimilation models to provide the strongest possible foundation for societal decisions pertaining to carbon and climate change. Linking with international efforts in the Northern Hemisphere is essential for resolving the North American contribution to global carbon sinks.

Reporting to the Nations of North America and the World

The NACP will sponsor a regular series of reports on the state of the carbon cycle that will identify, characterize, and quantify major regional sources and sinks of CO_2;

project future changes; and enable analysis of the effects of different management practices. These reports will present scientific findings to inform the public and support decision making on a continuing basis. The reports will be an evolving product that provide governmental and private stakeholders a synthesis of current data resources and knowledge on the science of the carbon cycle, with implications for economic and policy decisions. For the first phase of the program, the reports will focus on five deliverables:

- Explaining how the carbon cycle works
- Presenting emissions estimates and trends
- Producing regional-scale carbon inventories and flux estimates
- Assessing the potential of carbon management strategies
- Evaluating the stability of carbon storage.

Chapter 2: Major Elements

Major Elements of the NACP

Major program elements are noted briefly here, and elaborated on further in the following sections:

1(a). Develop the infrastructure of long-term observations of the atmosphere, including exchange fluxes with vegetation and soils. Ground-based, tower-based, aircraft, and satellite measurements will be combined to enable reliable estimates for U.S./North American sources and sinks of CO_2 and the other major carbon gases CH_4 and CO.

1(b). Develop and demonstrate the capability to measure net uptake or emissions of CO_2, CH_4, and CO from the land (forests, agriculture, urban and suburban areas, and wild lands) and ocean margins of North America. Intensive field programs will be a major focus. Results will provide essential scientific validation on local, regional, and continental scales of the CO_2 source/sink estimates from the long-term observation network.

2. Enhance (a) forest, crop, wetland, and soil inventories, and (b) process studies on land and in the ocean surrounding North America. Direct measurements of stocks and process mediating change are essential for quantifying fluxes, for validating models, and for constraining integrated analyses. Robust evaluations of the consequences of future emissions and policy options for carbon management depend on understanding the underlying processes of emission and uptake of CO_2 and CH_4.

3. Develop a new generation of atmospheric and ecosystem models to assimilate data from the program's observational components (atmospheric concentrations, meteorological fields, and observations of soils, vegetation, and adjacent ocean basins), to derive regionally resolved mass fluxes. The data sets that emerge from the program will be quantitatively and qualitatively different from current data, providing a three-dimensional picture of atmospheric concentrations at frequent intervals. The deduction of surface fluxes from these data requires a new class of models for atmospheric transport, linked to ecosystem and forestry models that incorporate advanced data assimilation methods.

The following sections survey these elements in greater detail.

Atmospheric Sampling Programs

Sources and sinks of CO_2, CH_4, and CO impart their signatures on the distribution of atmospheric concentrations, under the influence of atmospheric transport processes (e.g., advection, turbulent mixing, cloud venting). Thus the spatial and temporal distributions of CO_2, CH_4, and CO in the atmosphere provide spatially resolved information on surface-atmosphere fluxes over time, once atmospheric transport is accounted for.

This section discusses atmospheric observations to characterize the distributions of CO_2, CH_4, and CO that will serve as input for the analysis framework. There are two complementary components:

- A long-term network of atmospheric observations that provide the data set for target tracers to allow monitoring of trace gas sources and sinks over time. The network is intended to continue to function after the NACP ends.
- Intensive aircraft campaigns during targeted periods that yield enhanced observations to evaluate the representativeness of long-term network observations and to develop modeling and analysis tools.

(a) Network of Long-Term Atmospheric Observations

Guiding Principles for the Network. Long-term measurements of concentrations of CO_2, CH_4, and CO are currently made at a network of dispersed surface sites, each intended to represent air over a large region. Thus, most sites take samples at remote oceanic or desert locations, avoiding the influence of strong and variable sources and sinks on the continents. The purpose is to provide an accurate measure of global and hemispheric concentrations, including seasonal variations and long-term trends. Attempts to use these global data sets to infer net sources and sinks over North America have been limited by the absence of data from the interior of continents and near-shore environments.

Unfortunately, suitable data cannot be obtained by simply adding a few continental measurements to the existing network. Continental stations at ground level observe highly variable concentrations, reflecting the influence of proximate sources and sinks on the composition of the planetary boundary layer (PBL). This difficulty is only partially mitigated by making observations from tall towers, because even the tallest does not span the PBL on most days.

Tans et al. (1996) considered the characteristics of a network suitable for determining regionally resolved fluxes of the key gases. The requirements include vertical soundings through the PBL and into the middle troposphere using small aircraft, plus continuous measurements of fluxes and concentrations from both tall and short towers. Most aircraft soundings should be made with light planes equipped with simple, portable instruments to measure CO_2, CH_4, and CO; 2–4 stations in the network should have capable small jet aircraft with more sophisticated instrumentation and much greater range and ceiling. Corollary developments include specification of the actual vegetation cover and its physiological state and determination of the atmosphere-ocean fluxes in adjacent ocean basins.

Observations and models indicate that the correlation lengths for concentrations of CO_2, CH_4, and CO are typically about 1,000 km, similar to the size of weather systems. Thus, to determine an overall budget for North America we require a “ring” of stations along the coasts and through northern Canada, and stations in the interior at about 1,000 km spacing. These scales are suitable for measuring the influence on atmospheric CO_2 of regionally distributed processes, such as regrowth of forests in the eastern United States, agriculture in the Midwest, or woody encroachment in the Southwest. At least 20 sites would be needed across the conterminous United States, with lower density in deserts. The number needed in Canada and Mexico will depend on the goals and objectives established by those countries. A total of 30 sites for North America are anticipated.

The spatial density and the accuracy of the measurements must be adequate to distinguish signals due to uptake/release from other sources of variability. Consider uptake of CO_2 due to woody encroachment as an example. Pacala et al. (2001) estimated a notably high number, 0.12 GtC/yr, primarily in the Southwest. If spread out over an area the size of Texas, the annual mean decrease of CO_2 in the column would be 0.11 ppm/day. The signal would typically be concentrated in the boundary layer and lower free troposphere, and flushed out in about two days. The associated depletion in atmospheric CO_2 over 1,000 km could be 0.6 ppm in the lowest 3 km, comparable to the CO_2 from fossil fuels, which has to be carefully accounted for using other trace gases, especially CO. Our plan thus addresses the critical question of the capability of the measurements to define net fluxes from large-scale processes, such as woody encroachment, in the large-scale intensive experiments. The atmospheric “integral” would get increasingly difficult to use at scales of less than 1,000 km.

Vertical profiles should be obtained at a frequency of every other day, to avoid undersampling on the time scales for passage of weather systems, a major cause of variance of trace gas fluxes and concentrations. One could argue that two flights should be conducted each flight day to account for diurnal variations, but this is not yet certain. Perhaps co-located ground stations or towers could substitute. This question is a principal target of the large-scale intensives described below.

Measurements will have to be continuous in flight to allow sampling in controlled air space and to provide suitably accurate resolution of the PBL. A critical need for the program is to develop robust, easy-to-operate instruments for routine use in measuring CO_2, CO, and CH_4. Better instrumentation for CO_2, CH_4, and CO is needed for deployment on aircraft, at ground stations, on ships, and on tall towers. Likely more than 100 such instruments will be needed. Oceanographers and many others could put them to great use. Their development should not be delayed, otherwise the whole program will be impeded. Important contributions could be made also by total-column observations made using high-resolution upward-looking Fourier transform spectrometers, which can potentially determine very accurately changes over time in the vertical column amounts of CO_2, CH_4, CO, and other gases.

Fair-weather bias attends measurements made aboard aircraft, and observations are influenced by the fact that atmospheric variance, especially for CO_2, peaks close to the ground. Thus the PBL needs to be sampled as densely as possible. A network of tall towers, smaller AmeriFlux towers, and near-shore buoys should observe continuously. Tall towers provide robust statistical information on the covariance of the target gases under all weather conditions (Bakwin et al., 1998). Flux measurements, as in the AmeriFlux network, provide crucial biophysical information on the relationships between ecosystem types, flight days versus non-flight days, and uptake or emission of key carbon gases (Baldocchi et al., 2001) and on the covariance of target gases under all weather conditions (Potosnak et al., 1999). Hence towers allow adjustments for systematic errors associated with fair weather bias. Offshore aircraft profiles will be paired with continuous measurements from permanently moored buoys.

Flask samples provide quality control, especially for merging data from different stations, and allow measurement of other tracers and isotopes. Flasks should be deployed on a subset of flights, and at ground stations, for example, a set of 12 flasks could be obtained at each aircraft and 2 at each ground site at 10-day intervals

Phased Implementation of the Network. The observing system is designed to infer the magnitudes of sources and sinks of CO_2, CH_4, and CO from observed concentration differences, requiring analysis of regions sufficiently large that the impact of important postulated mechanisms for carbon storage or loss can be measured. We seek to discern the effects of current and historic land use and land management—for instance, an increase of organic matter in agricultural soils, regrowth of forests in the East, or woody encroachment in the Southwest. The effects of regional environmental anomalies, such as drought, cloudiness, air pollution, or changes in the length of the growing season, should be resolved. The design of the initial version of the observing system ought not to rely on atmospheric transport models to fill in sparse measurements.

An observing network of this kind has not been implemented previously. The design therefore includes phased development of new observations, with improved models to be applied continuously to such problems as optimizing network design and selecting sites. Early stages will demonstrate proof-of-concept by focusing on areas with already existing information on sources and sinks (e.g., for croplands), coordinated with intensive field studies to test instruments and develop infrastructure, personnel, and diagnostic models. Later stages will use knowledge from the early phases to refine the network design.

An initial conceptual plan for the phased implementation of the network is outlined in Appendix 1. Components include the following:

- Develop instrumentation to field-ready status by 2004, including robust, easy-to-operate sensors for CO_2 (infrared gas analyzer) and CH_4 and CO (candidate instruments include compact gas chromatograph or infrared analyzer).
- Install the network in a limited region of the central United States, with aircraft soundings about 500-1,000 km apart, tall towers, and flux towers. The season and region will be selected to have an already existing knowledge of net sources, such as during the growing season in a major wheat or corn area.
- Conduct an intensive field program that both covers the whole continent, with special focus on the region with the prototype network, to provide proof-of-concept, validate operational instrumentation, and similar activities.
- Expand the long-term network, periodically repeating the basic strategy in different seasons and different areas.
- Increasingly emphasize larger scales in associated intensive campaigns as the NACP develops.
- Test and validate models for analysis using these data.

Definition of an Observing Station. The ideal observing station has four components, not all of which will be realized at every site.

- **Repeated vertical profiles of continuous CO_2, CO, and CH_4 from small aircraft.** Experience with current observations has shown that ground-based data alone are hard to interpret. The variance is very large, produced by local sources and sinks as well as by atmospheric mixing and transport processes. Vertical profiles have lower variance than surface data and provide integrated measures of atmospheric column amounts that map directly onto net sources or sinks from large areas. Profiles of temperature and humidity provide information about the local mixing layer height, a key parameter to calculate average tracer values for the PBL. Most stations will acquire local vertical profiles using light aircraft, and a few will obtain more extensive vertical and horizontal data using small jet aircraft.
- **Upward-looking spectrometers to measure absorption of solar radiation in the mid- and near-IR**, where many trace gases as well as O_2 have strong spectral signatures. Total column amounts can be retrieved, with limited height resolution provided by pressure broadening of the line shape. Diurnal variations are recorded, providing a measure of diurnal bias for the aircraft soundings, which will cover only one to two hours of the day. Extensive initial calibrations of the profiles derived from spectra will be necessary through in situ measurements on aircraft. The spectrometers will measure a wide range of species beyond CO_2, CH_4,

and CO, including O_3, NO_2, SO_2, CFCs, and other gases. Thus these instruments will have wide application beyond carbon cycle studies, especially in studies of air pollution and ozone-depleting gases.

- **All-weather continuous measurements of trace gases and meteorological parameters** can be made on tall TV transmitters, from the ground to 400 m altitude. Ideally, a robust and inexpensive probe of boundary layer height can be developed. These data address the bias against cloudy conditions that attends both aircraft and solar absorption measurements.
- **All-weather continuous measurements at smaller towers** define the covariance of fluxes with environmental conditions, and the covariance among target gases, also free of bias against cloudiness and time of day. Simultaneous observations of CO_2 mixing ratio and surface flux may allow precise extrapolation of surface layer mixing ratios to mid-PBL values, and data on the covariance of CO_2, CH_4, CO, and other gases are obtained.

(b) Intensive Atmospheric Field Campaigns

Intensive field programs (intensive operation periods, IOPs) are part of the phased implementation of new continental observations. Currently we have only rough estimates of the spatial and temporal sampling density needed to resolve seasonal and annual budgets for CO_2, CH_4, and CO, based on limited field data (e.g., the recent CO_2 Budget and Rectification Airborne Study, COBRA 2000; see example data below) and model runs. The IOPs will combine deployments of research aircraft, biophysical studies, development of models and analysis tools, and remote sensing to address critical subsets of research questions required for the program. The enriched sets of data will help to determine how well data from the long-term stations (element 1, page 13) represent ambient distributions, and to evaluate the accuracy of tracer budgets computed from the data of the long-term network. Enhanced data sets from the IOPs will also help develop and test models described in element 3 and help to constrain bottom-up scaling approaches driven by biophysical data (elements 2 and 3, page 13).

- *Strategies for Intensive Sampling*. Comprehensive aircraft observations are required to provide the necessary vertical and horizontal spatial coverage of tracer distributions. The proposed intensive studies will carry out in situ airborne measurements of CO_2, CH_4, CO, and a suite of related gases in the lower- and mid-troposphere of the selected regions of North America, covering spatial scales from regional (100-500 km) to continental (1,000-5,000 km), extending over adjacent ocean areas. The strategy consists of the following complementary approaches:

- *Regional budget experiments.* Diurnal airborne concentration measurements of CO_2, CH_4, CO, and H_2O will be carried out within and above the PBL in a Lagrangian (airmass-following) framework, in areas selected to include the best possible sets of complementary data (e.g., tower observations, crop models) and stations of the long-term network. Detailed analysis of the underlying vegetation will be carried out, typically utilizing remote sensing and data from tall towers and flux towers. High-resolution meteorological models will be used to analyze these data to yield regional fluxes and their variations across different landscapes. The Lagrangian approach minimizes artifacts associated with unaccounted advective fluxes. Concurrent airborne eddy flux measurements in the same air mass can provide spatially resolved fluxes on even finer scales. Experiments at these scales are designed to test the ecosystem and biophysical models developed for the overall budget analysis and to validate co-located elements of the long-term network.
- *Vertical profiles repeated frequently over selected locations in a focus region*. Measurements of frequent vertical profiles show changes in column amounts of target gases during the day, yielding first-order estimates of fluxes of carbon gases when analyzed using data assimilation tools. These measurements are similar to those of the long-term network, but they cover all hours of the day, higher altitudes, transits within the PBL, and upwind and downwind locations. Ground-based surveys using mobile sensors and surface meteorology can be used to map sources and sinks of CO_2, CH_4, and CO. The measurements allow direct assessment of how well the routine profiles represent regional concentrations and budgets, and testing the network sampling design for diurnal and spatial biases.
- *Large-scale surveys.* Plans include sampling of large-scale distributions of CO_2, CH_4, CO, and H_2O within

and above the PBL, across large regions, up to continental scale, and out into the eastern North Pacific and western North Atlantic. These data allow tests of the long-term network and its analysis framework, including representation of inflow boundary conditions and effects of long-range transport of air pollution. They provide strong constraints on inverse models for the time period of the intensives, allowing evaluation of budgets by inversion of the network data set only. Flight tests of airborne versions of planned remote sensing instruments will be carried out. The missions promise strong two-way benefits from joint deployments with atmospheric chemistry experiments (see the section on synergy below).

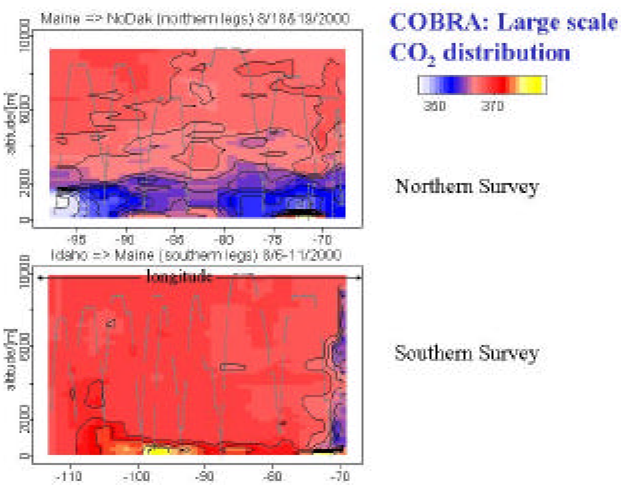

Figure 2. Concentration distributions for CO_2 across the northern tier (upper) and southeast/central state (lower) acquired in August 2000, in the CO_2 Boundary -layer Regional Airborne experiment (COBRA-2000) (Gerbig et al., 2001).

The concepts to be implemented in the IOPs received preliminary tests in a pilot study (COBRA 2000; Figure 2) conducted over North America in July 2000. The observations, shown as contour plots against altitude and longitude (left panel), demonstrated that the signals of underlying sources and sinks are measured unambiguously and quantitatively in the atmosphere. Distinct vertical contrasts were observed between the PBL and the overlying atmosphere. Atmospheric distributions of CO_2 and CO were regionally coherent and reflecting activity of the underlying vegetation, such as regions with growing (northern transect) versus dormant vegetation (southern transect) (cf. vegetation status map, right panel).

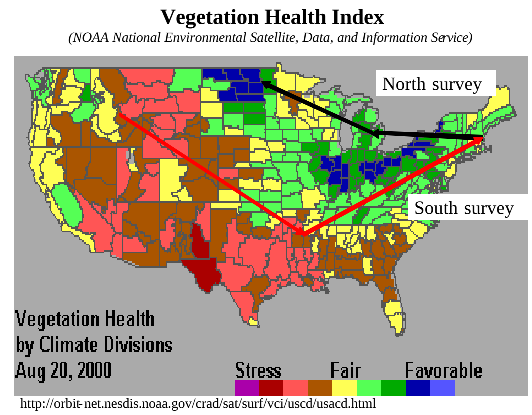

Figure 3. NOAA's Vegetation Health Index for the time period of the measurements in COBRA-2000.

- *Phased Implementation of Intensives.* Implementation of intensive measurements to evaluate the long-term network represents a difficult scientific challenge. Field measurements must be phased according to the development of the continuous network, providing assessments of gaps in the routine data sets that help to refine the concepts and implementation. Early phases will include two intensives designed as proof-of-concept for retrieving regional-scale emissions from concentrations. The focus will be on regions where the first phase of the long-term network is implemented. Later phases will seek to close budgets for tracer species for a critical seasonal period and to target regions guided by advances in biophysical knowledge, such as contrast areas where the land surface is a sink versus where it is a source. Further, target areas will be selected where extensive flights will be conducted to generate the data set with the spatial resolution necessary to constrain bottom-up estimates of surface fluxes (at about a 10-km scale).

Large-scale measurements in all NACP phases will link up with airborne observations from coordinated atmospheric missions such as NASA's Global Tropospheric Experiment, and proposed NCAR and NOAA experiments. Appendix 1 illustrates possible configurations and mission profiles envisioned for the intensive program of measurements.

Land: Measurements and Models of Terrestrial Carbon Fluxes

Motivation

Large-scale carbon fluxes among land ecosystems, the atmosphere, and the ocean reflect the responses of diverse ecosystems to climate, soils, natural disturbances, and direct and indirect human perturbations, including air pollution, elevated atmospheric CO_2, and land use and management. The size and distribution of carbon stocks are roughly known for the major ecosystem types in the United States. However, knowledge of changes in stocks, and the mechanisms that cause such change, is far from complete.

Changes in soil carbon control net ecosystem carbon flux in many non-forested ecosystems such as grasslands, croplands, and wetlands, which comprise two-thirds of the land surface in North America. In forests and woodlands, changes in C stocks can be significant in live or dead biomass, or in soils. Carbon stocks in soils and vegetation may respond differently to environmental changes. Carbon fluxes are especially poorly documented for important ecosystems with limited commercial exploitation. For example, increases in woody vegetation in grasslands and savannas, resulting from long-term suppression of fire, appear to be a significant carbon sink (Pacala et al., 2001), but few data are available.

Peatlands are another poorly known but potentially important ecosystem, covering 12% of the land in North America. Net primary production is low, but stocks of soil carbon are huge (Harden et al., 1992), with approximately 455 PgC (about 60% of the C in the atmosphere) stored within 1 meter of the surface. Peatlands and wetlands are also major sources of CH_4 (e.g., Crill et al., 2000). Peatlands are vulnerable to small changes in climate. Changes in temperature, evaporation, precipitation, or hydrology can quickly change a peatland from a small sink for atmospheric CO_2 and a source of CH_4, to a strong source of CO_2 and a small sink for CH_4.

Over 70% of CH_4 emissions are anthropogenic, dominated by biogenic sources (e.g., landfills, domestic sewage, rice agriculture, ruminants, animal waste), with a smaller amount associated with fossil energy. Agriculture accounts for about 50% of human-related CH_4 sources globally, about 30% in the United States. Agricultural sources of methane include concentrated (e.g., feedlot) and diffuse (non–point source) emissions, and are sensitive to production practices such as applications of water, fertilizers, and manures. Determination of agricultural methane emissions is needed to quantify the North American and global carbon budgets.

Natural wetlands account for more than 20% of the global CH_4 source, largely northern peatlands and tropical wetlands. CH_4 exchange from these environments is intimately linked to hydrology, system productivity, and carbon accumulation and balance. At the regional scale, CH_4 emissions for many landscapes in North America are dominated by natural sources (termites, wetlands, lakes and coastal waters). Different mixes of anthropogenic and natural sources and sinks determine the net fluxes in different regions. For example, in New England, northern peatland sources dominate CH_4 emissions in Maine, but landfills and energy use dominate in Massachusetts and the south.

Historical legacies of natural disturbances and past land use and land management appear to play a large role in the long-term carbon balance of North America. Forest and agricultural inventories, historical data on forest harvesting and clearing, and agriculture can all provide clues to historical factors that regulate carbon fluxes. Currently incomplete historical records and limited process understanding generate substantial uncertainty in the fraction of the current carbon sink in U.S. forests that can be attributed to the trajectory of land use and land management (e.g., Pacala et al., 2001). Natural disturbances, including severe storms, fire, and insect outbreaks, appear to be important also (Kurz and Apps, 1999) and may be increasingly important in the future.

Objectives for Enhanced Measurements and Models on Land

The goals for NACP ecosystem measurements and models are to quantify, and reduce uncertainty in, spatial patterns and mechanisms accounting for changes in carbon stocks and CH_4 release and uptake. The effort is intended to make a critical contribution to integrated analysis of the North American carbon balance.

Principal associated research objectives for NACP terrestrial studies include the following:

- Improve ongoing inventory and monitoring of national greenhouse gas emissions from land.

- Develop well-quantified large-scale estimates of C exchange with the atmosphere.
- Improve the ability to attribute observed changes to the full suite of mechanisms, including natural variability as well as direct and indirect human influences.
- Provide the information on plant and soil components of ecosystem carbon fluxes necessary to understand and interpret larger scale regional and continental fluxes.

The long-term observational strategy should include several elements:

- Identify gaps in current sampling strategies, stratifying by climate, biome, management, and land-use history.
- Enhance established networks or begin new activities to fill gaps using ground-based techniques and remote sensing.
- Extend the time scale for flux data for soils and vegetation, and make the coverage of ecosystems more comprehensive, stratified by region, climate, biome, and management history.
- Fully exploit and efficiently manage existing data, with better acquisition, assimilation, analysis, and dissemination.
- Assemble and distribute ancillary data sets needed for interpretation, including data on vegetation, soils, climate, hydrology, and land management history.
- Improve ecosystem and land-use models to interface with the data assimilation concepts (element 3).

Except for CO_2 flux towers, current land surface observations do not explicitly measure or monitor changes in C stocks (or *fluxes*). The data therefore lack critical features, including lack of complete ecosystem C measurements (particularly below-ground C), gaps in spatial coverage, inconsistent procedures relative to time and location, and lack of sufficient temporal resolution (re-measurement intervals as long as 15 years in important areas). The NACP plan will address this issue by including quantification of carbon stocks and fluxes as a key objective for ecosystem measurements at all scales.

Advances in modeling, such as newly emerging dynamic global vegetation models (DGVMs) and high-resolution biophysical models, may play important roles in integrating land and atmospheric data. The key will be to link spatial and temporal scales up to continental (or larger) and decadal (or longer) scales. A major goal of the NACP is to develop new frameworks for cross-scale connections, and to link biophysical studies of the carbon cycle with socioeconomic models that address the needs of policy makers and land managers.

Implementation of Biophysical Measurements: A Hierarchical Approach

Diverse data on land ecosystems, collected at a range of temporal and spatial scales, are required to determine regional- and continental-scale carbon exchange. The data must be integrated within a comprehensive framework that includes statistical scaling techniques as well as process models. Sources of data will include reconstructions of land use and land management history, past and ongoing resource inventories, satellite remote sensing, as well as process studies, including ecosystem gas exchange with eddy covariance.

Land use records and inventory measurements have low temporal resolution (5-10 years), but sampling density can be very high, with more than 100,000 sites in some networks. Data from eddy covariance sites provide information with very high temporal resolution (30 minutes) at a few (about 40) sites. Satellite data cover the whole landscape at frequent intervals, but the data are only indirectly related to carbon fluxes. Remote sensing with the highest temporal resolution, but moderate spatial resolution (e.g., from MODIS), enables extension of process-based simulations, while high spatial resolution but lower temporal resolution data (e.g., LandSat) are best to define land use and management.

Extensive observations are critical because the land surface is so diverse. Given the clear importance of vegetation, climate, soils, natural disturbance, and land use history, every plot can potentially have a unique carbon balance. Without the comprehensive coverage provided by remote-sensing data and inventories, it is exceedingly difficult to constrain the carbon balance of a large region. But interpreting the extensive data is impossible without calibration and understanding from intensive studies at selected sites. Observations at intensive study sites complement large-scale data in at least five ways. First, they provide a context for testing hypotheses about mechanisms. Second, they serve as a test bed for model development and testing. Third, they function as test sites for evaluating extensive methods, including methods based on both inventories and remote sensing. Fourth, they provide data that are unique in terms of both processes covered and accuracy for comprehensive analysis with data fusion. Finally, intensive sites can serve as test sites or controls for experiments aimed at enhancing carbon storage.

Since intensive studies are impractical at more than a few hundred sites, the NACP will use a hierarchical approach to land research, integrating four networks spanning intensive to comprehensive. This hierarchy will:

- Link observations across space and time using a nested design
- Link observations with understanding from process studies
- Carefully select and define parameters for integration
- Include all representative major land cover and land use types
- Provide means to estimate critical variables for understanding and quantifying C fluxes
- Measure common variables across tiers using standard protocols
- Implement strong QA/QC at all sample phases, and quantify estimation errors
- Dynamically couple atmospheric, biospheric, and human systems
- Advance the state-of-the-art for integrated models and analysis.

The large-scale land monitoring programs will adopt a sampling strategy with four tiers distinguished by spatial averaging, resampling frequency, and type of observations. Some data elements are identically defined and collected at each tier, providing direct links among tiers, while other variables may be unique to one or a subset of tiers. The combination of remote sensing, extensive inventories, medium-intensity sampling, and intensive observations at selected sites together comprises a powerful, flexible, and potentially efficient data collection system. The sample tiers must, however, be linked statistically so that inferences about the entire population within cover classes can be made. The observation system should have the capability to closely integrate with atmospheric monitoring, but should also stand alone to provide independent estimates of C fluxes for validation and as a contribution to ecosystem science.

Multi-tiered sampling and analysis has previously been implemented for land inventories and, more recently, for linking new remote sensors with field data. The first tier of the NACP involves comprehensive measurements with remote sensing at continental scale. Middle tiers include (tier 2) existing, densely sampled, extensive land inventories composed of a large number of sample plots, and (tier 3) a proposed new set of approximately 1,000 medium-intensity plots with process monitoring at medium-intensity sites, also selected to represent typical conditions across the landscape. The fourth tier includes the existing and potentially new intensive observation sites where the most detailed observation are made, such as at LTER and AmeriFlux sites.

Table 1 illustrates the multi-tier concept with a listing of a few of the variables likely to be central to the land observation system.

Table 1

Example Data Elements	**1st Tier** Mapping and Remote Sensing	**2nd Tier** Extensive Inventory (FIA and NRI)	**3rd Tier** Medium-Intensity Sample (new)	**4th Tier** Intensive sites (e.g., AmeriFlux)
Land cover class	X	X	X	X
Leaf area index	X	X	X	X
Live biomass	X	X	X	X
Land cover change	X	X	X	
Wildfire disturbance	X	X	X	
Climate variability			X	X
Soil CO_2 flux			X	X
Methane flux			X	X
Dissolved organic C				X
Ecosystem CO_2 flux				X

NACP implementation envisions that a complete and well-defined set of variables will be phased in systematically over three to five years. During implementation, appropriate estimators will be defined through modeling and analytical studies, and recommendations made for enhancing observations to produce an efficient, continuing multi-tier network optimized for estimating C flux at multiple temporal and spatial scales. An efficient way to integrate across scales is not apparent for some critical variables such as soil CO_2 and methane flux. Preliminary studies and pilot implementation tests will be undertaken to develop a strategy for these variables.

The following summary shows how the hierarchy of networks will link observations and understanding across space and time, carefully stratified to ensure appropriate coverage of climate, soils, vegetation, disturbance, and land use history. The intent is to link networks with coordinated observations and analysis, implement strong QA/QC at all levels, quantify estimation errors, and provide appropriate inputs for data fusion through diagnostic models and analysis.

Tier 1: Comprehensive Measurements with Remote Sensing. Current U.S. land inventory systems use a combination of high-altitude aerial photography and Landsat Thematic Mapper (TM) data to sample the largest scale and to detect change. Several sensors with coarse spatial resolution but high temporal resolution have been used to drive terrestrial biogeochemistry models that estimate carbon stocks and fluxes, typically with limited information on land use history. Products from the 20-year record of NOAA AVHRR (advanced very-high-resolution radiometer) data provide a picture of recent temporal dynamics. SeaWiFS provides a vegetation index of higher quality but for a shorter record (Behrenfeld et al., 2001). The NASA MODIS sensor, launched in 1999, should provide data of very high quality over the coming years, enabling a number of new biogeochemical models (Running et al., 1995).

Additional sensors in the planning stage will provide new information, including aspects of canopy chemistry and structure and soil moisture. The Vegetation Canopy LIDAR (VCL) is a promising sensor. VCL data may provide estimates of above-ground biomass, an important quantity in the carbon budget that has been beyond the scope of most remote-sensing analysis. Enhanced utilization of remote-sensor data is also needed. Data on land use and cover (from LandSat) need to be better integrated with the data from AVHRR, SeaWiFS, and other satellites with high temporal resolution, and remote-sensing data need to be better informed by historical, atmospheric, and weather data. The range and quality of remote-sensing data products need improvement.

Several specific needs have been identified to provide data to the NACP on carbon stocks at tier 1, using remote-sensing products and in situ data: (1) timely systematic and routine processing of satellite data from the North American continent into land cover and land cover change products, covering both natural and human disturbances; (2) integration of satellite observations with in situ measurements of carbon stocks and existing inventories; (3) augmentation of satellite and in situ estimates of carbon stocks with airborne and surface measurements; and (4) development of appropriate estimation models.

Additional details about remote-sensing contributions to the NACP are included in Appendix 4a.

Tier 2: Dense Sampling with Inventory Techniques. Current large-scale land inventories conducted by USDA, the Forest Inventory Analysis (FIA) and National Resources Inventory (NRI), employ multi-tier sampling strategies using remote-sensing and ground measurements. These continuous inventories provide baseline information about land cover, management intensity, productivity, and disturbance that can be used to estimate carbon stock changes over 5 to 10 year periods. Very high sampling intensity allows detailed description of some of the causes of observed carbon stock changes, such as the effects of vegetation growth, mortality, and harvesting. Historical data are available to trace land use and management history.

Current land inventories are limited in several critical ways: incomplete coverage of regions and ecosystem types; lack of complete ecosystem C measurements; limited temporal resolution; and lack of easily available and usable historical data. There is little or no coverage of some “reserved” areas: lightly sampled areas of the Intermountain West, the Pacific Coast, Alaska, urban, and suburban areas; and large areas of public non-forest land (mostly grazing land in the West). Large areas of Canada and Mexico have been sparsely sampled. Enhancements to ongoing inventories are projected to fill some of these gaps, especially in forests, but others remain.

Carbon pools that are poorly quantified in existing inventories include stumps, live and dead roots, mineral soil, litter, and coarse woody debris. Land inventories are generally designed to provide a "rolling average" estimate with a temporal resolution of 5 to 10 years, sufficient for some applications, incompatible with the temporal resolution needed by the NACP.

New designs for forest inventories address temporal resolution using successive sample "panels" to approximate continuous sampling. Each panel is re-sampled with a period of 5 to 10 years. Supplemental data with higher time resolution are merged with the inventory data to estimate the major causes of variations in C flux—productivity, mortality, harvest, and land use change—using advanced statistical techniques to estimate annual changes in C stocks. Sources of supplemental data include flux towers (productivity and trace gas dynamics), aerial and satellite disturbance surveys (land use change, damage and mortality), and timber and agricultural product surveys (harvest quantities).

Some of the existing sites for intensive studies (e.g., LTER and Ameriflux) are not monitored with inventory techniques, inhibiting the extension of results of intensive studies using inventories. This is especially true for terms like soil CO_2 flux and CH_4 flux, which are beyond the scope of traditional inventories. New direct measurements of C fluxes will be needed during intensive field programs, and in the new medium-intensity sampling network (tier 3).

Tier 3: Process Monitoring at Medium-Intensity Sites. To take full advantage of comprehensive remote-sensing data (tier 1) and extensive inventories (tier 2) will require a set of sites of intermediate intensity and number. It is not practical to deploy intensive sites in all of the nation's ecosystem types and across the full range of land use histories. Yet, process data from this entire range is crucial for robust analysis. A new network of approximately 1,000 medium-intensity sites is planned to provide appropriate coverage.

Measurements at these sites should address the major processes in the carbon balance, including net primary productivity (NPP), leaf area index, leaf nutrients, soil respiration, litterfall, dynamics of coarse woody debris, and CH_4 flux. Depending on technology development, it may be practical to measure C balance with eddy flux at many of these sites. It will be important to obtain accurate records of land use, including past history as well as current management. Environmental conditions, including soil moisture and solar radiation, should be measured at each site to facilitate assessment with ecosystem models.

The new tier 3 sites will serve as invaluable links between the approximately 100 intensive sites and the much larger number of inventory sites. Because tier 3 sites will directly measure components of carbon balance, they will be a centerpiece for testing models developed at the intensive sites. Direct measures of components of the carbon balance will also be critical for setting appropriate conversion factors for the quantities that need to be estimated in inventories.

Tier 4. Mechanistic and Process Studies at Intensive Measurement Sites. Intensive sites provide direct estimates of C flux and C stock changes across a range of temporal scales. In addition, research at these sites will include detailed studies on the mechanisms controlling the fluxes. Data from intensive sites will be critical for developing and testing models, for interpreting large-scale patterns, and for constraining data fusion models.

Many of the approximately 100 intensive sites that will be needed are already in place. Net ecosystem CO_2 exchange is presently measured at more than 30 sites in North America that are part of the AmeriFlux network. Additional sites are planned in the Flux-Canada network. Only a few sites are currently making the complete range of measurements that will be needed for the NACP. Enhancements will be necessary to insure that all of the flux sites measure the full range of controlling variables and that they also deploy all of the measurements used in tier 1, 2 and 3 sites.

Flux tower sites. Net ecosystem CO_2 exchange is presently measured at more than 30 sites in North America in the AmeriFlux network (supported largely by DOE through the Terrestrial Carbon program and the National Institute for Global Environmental Change). Additional sites are planned in the Flux-Canada network. Summed over the course of a month, season, or year, data from these sites provide direct measures of ecosystem CO_2 source or sink strengths. In contrast to the network of tall towers described under element 1, most flux towers are "small" (<60 m) and provide information specific to one ecosystem type.

Data from flux sites help test physiological models of C exchange and are critical to relating fluxes and remote-sensing data. Companion physiological and ecological measurements enable partitioning carbon fluxes into plant and soil components and reveal mechanisms responsible for these fluxes. At some sites, biomass-based estimates of C storage have validated C budgets from direct flux data (e.g., Curtis et al., 2002; Barford et al., 2001). Data from the flux sites have been applied in ecology, weather forecasting, and climate studies, especially for sites with several years of data to quantify interannual flux variations.

Important enhancements are required for this network in the NACP:

- The present network of flux sites must be augmented in both capacity and number to achieve the goals of the NACP. Sites that cover under-represented ecosystems, land use history, and current management are needed, including actively managed cropland, forest, pasture, and arid ecosystems, as well as studies in Mexico and northern Canada.
- Data will need to be transmitted rapidly to an available data center. This development will enable the measurements to be used in data assimilation activities (see below).
- Flux sites will need to carry out continuous, high-precision measurements of atmospheric CO_2, CO, and CH_4 concentrations. Presently only a few sites do these measurements, which provide continuous data sets representing covariances among the key species in a region. These data have not yet been accepted into the CMDL database (more QA/QC is needed).
- Flux sites need to include a consistent suite of biophysical measurements to characterize the sites for synthesis and for linking with other measurement systems. Some important measurements include biomass stock, species composition, soil C stock, and annual NPP.
- Network structure should be strengthened. The AmeriFlux network has grown on an ad hoc basis with individual sites funded by a variety of agencies and programs. Coordination is voluntary, and consists of standard and recommended measurements, data handling, adherence to quality control procedures, and deposit of data with CDIAC. A more formal structure, with defined site selection, QA/QC, review, and analysis procedures, would appear to be desirable. Only a limited number of sites have been able to obtain long-term, high-quality data with consistent procedures.

At least one-third of North America is topographically too complex for eddy flux measurements, and gaps will have to be filled using remote sensing, The Tier 2 intermediate sites, and modeling techniques (see “data assimilation”, below).

FACE, LTER, and agricultural study sites. The National Science Foundation’s Long-Term Ecological Research (LTER) sites can contribute to understanding terrestrial C budgets. Some include unique measurements such as dissolved organic C and particulate C losses. Existing long-term agricultural experiments provide another major resource. The CASMGS (Consortium for Agricultural Soils Mitigation of Greenhouse Gases) program involves a number of USDA and University Experiment Station long-term sites, focused on soil management decision-making issues. Free Air Carbon Exchange (FACE) experiments examine stimulation of ecosystems by elevated CO_2. Enhanced instrumentation on a number of these sites, adding tower- and chamber-based measurements of CO_2 and CH_4 fluxes, isotopic measurements to support understanding, and modeling the controls on carbon cycling, are envisioned as parts of the NACP.

New intensive observation sites. In addition to enhancement of current sites, the new intensive sites will be needed to sample under-represented ecosystems and patterns of land use and current management. Additional sites will be needed in actively managed cropland, pasture, and arid ecosystems, as well as in Mexico and northern Canada.

The tier 4 sites will need strong coordination to function with a high level of reliability and quality control. In addition, key sites should be networked to deliver data in near real time, facilitating the prospects for real-time analysis. A more formal structure than exists at present, with defined site selection, QA/QC, review, and analysis procedures, will be necessary for NACP. At least one-third of North America is topographically too complex for eddy flux. Developing methods for obtaining tier 4 data from these regions is a key priority that needs to be addressed at the start of the NACP.

Tier 4 measurements of terrestrial sources of methane. Atmospheric measurements of CH_4 should be complemented by surface observations at representative sites to enable optimal evaluation of source/sinks, and to quantitatively resolve the major elements that produce the net flux. Identification of sources and long time series of data are required to quantify causes of variability and to resolve emission processes at interannual or longer time scales.

Between 1 and 12 million hectares of forest and other vegetation burn annually in North America, resulting in emission of 40–200 Tg of carbon as CO_2, CH_4, CO, and other trace gases. These emissions represent a potentially major source of error in the analysis of atmospheric measurements, and they may make significant contributions to annual budgets for North America. Large fires in Mexico, the coterminous U.S., Canada, Alaska, and even Russia produce emission plumes in the study region with significant enhancements of concentration. Significant research is now focused on developing methods to collect the required data and to model emissions from biomass burning, but considerable uncertainties need to be addressed in the near term.

Data Assimilation, Analysis and Models

The Data Assimilation Challenge. This section outlines the development of the soil and plant components of an integrated data assimilation framework for the C cycle, built on closely coupled, data-driven models for the atmosphere, soils and plants. The atmospheric components, and the links between biophysical and atmospheric components, are discussed elsewhere in this document.

The challenge is to define a vegetation-soil-biogeochemistry modeling framework that can interface optimally with input data from diverse sources. In principle, a model in this framework could be as complex as nature itself, with countless parameters, but we must develop a diagnostic model whose parameters can be constrained by observations, focusing on quantitatively defining those processes that regulate the key emergent properties of the ecosystem (fluxes, stocks, structure) on the relevant time scales (hours, years, decades). Models within this framework will be used, to analyze data from the NACP using conventional methods and full-system assimilation methods, and will function prognostically when linked to climate models for the future.

Features must include improved estimates of carbon stocks in soils and in natural and managed vegetation, and accounting for prior disturbance, nutrient limitations and inputs, pollution, extreme meteorological events, chronic and acute stress and herbivory, and invasive species. Considerable effort will be needed to design this new class of model, including observations and manipulations to test the models over long and short time scales.

Input to biophysical models. Historical land use, exposure to air pollution and deposition, severe weather, insect outbreaks, and management are key factors explaining current observed terrestrial CO_2 fluxes and associated ecosystem structure, including age class distribution, soil fertility, and species composition. Historical data in a spatially explicit database are essential inputs for models. A project to develop a prototype of such a database has begun, with special attention to historical information about selected intensive study areas. It will be a dynamic database, updated using remote sensing and enhanced inventories outlined in the previous section. The goal is an accurate, high-resolution, time-varying map of land cover and land use in North America, with the following data:

- Land cover, land use, and management intensity
- Current vegetation type, community structure, age classes, Leaf Area Index (LAI)
- Vegetation biomass, live and dead
- Soil physical properties (texture, water/thermal capacities, etc.)
- Soil chemical properties (carbon, nitrogen, phosphorus pools in organic matter; inorganic C)
- Topography and geographic boundaries
- Climate (temperature, precipitation, humidity, wind, etc.)
- Atmospheric deposition (ozone, N)
- Natural disturbances (wildfire, insects, weather).

These data are the foundation of biophysical/ biogeochemical models.

Structure of biophysical/biogeochemical models. Biogeochemical models simulating fluxes of mass (CO_2, H_2O, and CH_4) and energy, productivity, respiration, and effects of disturbance will be driven by data from three sources: (1) the dynamic map of land cover/land use/inventories establishes the slowly varying state variables of the ecosystem (stock, vegetation, soils) at each grid point; (2) remote-sensing and in situ biophysical data provide current values of a subset of transient state variables of the system (soil moisture, phenology, recent events such as drought, wind, ice); and (3) atmospheric data (from satellites and assimilated meteorological products) provide drivers for ecosystem processes (sunlight, evaporation, temperature, precipitation). It is very advantageous to maintain consistency in the conceptual framework and driving data across the diverse spatial and temporal scales applicable to biophysical or biogeochemical models.

Land surface biophysical models will ideally be driven at time steps of about 1 hr to provide temporally and spatially complete estimates of surface CO_2 and CH_4 flux comparable with aircraft data. The models must first accurately compute energy and water balances for the major vegetation and climatic regimes on the continent and in the coastal ocean. The model then must compute hourly CO_2 and CH_4 inputs and outputs, that is, photosynthetic uptake and autotrophic and heterotrophic production of CO_2 and CH_4. Nutrient cycling and other long-term factors (e.g., vegetation structure, soil organic carbon, and permafrost) must be dynamically treated.

The NACP requires realistic simulation of fluxes for time scales shorter than a day using an "ecological data assimilation" approach. Each iteration updates from the previous time step using ongoing satellite data and in situ observations (mainly from AmeriFlux sites). AmeriFlux and satellite data will have to reach a central location promptly. A pilot study is currently underway in which MODIS data are obtained weekly for evaluation. There is clearly much work to be done, though, to obtain daily or hourly downloads, and the uniformity and reliability of the AmeriFlux data products require improvement. Many remote-sensing data products are currently available, or expected by 2004, including the following at 1 km resolution: snow cover, albedo, surface evaporation resistance (for energy partitioning, LAI and FPAR, or Fraction of absorbed Photosynthetically Active Radiation), GPP (Gross Primary Product, for defining regional gradients and phenology), fire area coverage and plume dispersion, and surface moisture/wetlands delineation/drainage class.

Models will need to deliver outputs of hourly values for surface CO_2 flux, GPP, NPP, (Net Ecosystem Exchange (NEE), and fluxes of CO_2, CH_4 and latent heat, respiration components, water and energy balances (hourly and daily), albedo, roughness, and so forth at about 10 x 10 km resolution, to function optimally with aircraft and meteorological data.

At least one-third of North America is topographically too complex for eddy flux towers or low-altitude aircraft measurements. These areas are generally forested with significant potential for sources or sinks of carbon. A multi-step procedure will be needed to derive NEE values for these regions, lacking flux measurements. Remote-sensing data will provide land cover and weekly GPP (MODIS). Daily surface meteorology from the National Weather Service can be extrapolated using topo-climatology principles, such as elevational lapse rates and aspect to map the surface microclimate. Then, photosynthesis, autotrophic and heterotrophic respiration can be computed. Model-based estimates of NEE in the mountains may best be tested using gauged watersheds to estimate hydrologic fluxes, and biomass inventories to validate carbon fluxes. This procedure is not as direct a test of surface NEE as are flux data, but can provide complete and consistent NEE estimates for mountain areas suitable for deriving regional and continental flux data from NACP atmospheric measurements.

Complete Carbon Accounting. Carbon may be transported in or out of an analysis region through erosion/sedimentation or product harvest (crops, timber). Hence, atmospheric estimates must be carefully matched with complementary accounting for fluxes on the land. Also, deposition or mobilization of inorganic C in soil as carbonates can play a significant role, especially in arid and semi-arid soils, and must be considered in C transfers between land, atmosphere, and oceans.

Data Management. Many of the required data streams exist today, but are not produced consistently at the time/space resolution needed, and the data are not assembled into an integrated set for data fusion. Because of the diversity of data and multiple temporal and spatial scales, it will be a significant challenge to make these data available for data assimilation activities and for public use. Hence, enabling activities are needed in this area.

Oceans: Measurements and Models of Marine Carbon Fluxes

The Ocean and the North American Carbon Cycle

The oceans absorb half of the 4 to 5 Pg C sequestered annually from the atmosphere. The location and year-to-year variations of marine carbon uptake are uncertain. Carbon exchange between the atmosphere and ocean is caused by a variety of physical effects and ecosystem responses to weather, climate, and land-ocean interactions. Large-scale climate shifts (e.g., El Niño, the

Pacific Decadal Oscillation and North Atlantic Oscillation) cause variability in regional fluxes and distributions of CO_2 in waters surrounding North America, with potentially important implications for efforts to measure net carbon fluxes for the continent.

Ocean programs generally focus on open ocean processes, thus missing the CO_2 exchange along the ocean margins that can affect the CO_2 content of air entering or leaving North America. Coastal upwelling and biological production rates are high in these regions, which also receive large carbon fluxes from rivers. In addition, a large fraction of the ocean's surface waters may acquire the chemical and biological characteristics that control net CO_2 exchange via margin processes. Thus, the influence of nearshore processes may extend beyond the geographic boundaries of ocean margins. The North American Carbon Program therefore requires marine observations and diagnostic models focused on understanding the role of coastal systems on adjacent ocean basins and on atmospheric CO_2 distributions.

Climatic perturbations may affect the coastal ocean quite differently than the open ocean. For example, when sea surface temperatures in the open ocean increase in an ENSO (El Niño–Southern Oscillation) event, CO_2 evasion may increase due to higher surface water pCO_2. But ENSO events can sharply decrease upwelling in coastal regions, reducing CO_2 out-gassing. Meteorological and long-term (land use) influences on runoff have dramatic impacts on nutrient inputs and the export flux of carbon in coastal margins. Runoff changes resulting from ENSO events may also change the partitioning of material discharged to the ocean, and impact fluxes of DOC, POC, and DIC to the ocean. Because of the sensitivity to changes in winds, river runoff, and anthropogenic inputs of nutrients, the CO_2 fluxes in nearshore waters will likely respond strongly to climate change.

The Marine Component of the NACP

The oceans component of the NACP is designed to leverage the impressive suite of existing and developing marine programs on the carbon cycle (see Appendix 3 for a summary), to define the role of the oceanic regions bordering North America. The main objective will be to provide information on processes controlling seasonal and interannual air-sea CO_2 fluxes within ocean margins and ocean basins adjacent to North America, to define the net effect of the marine system on the CO_2 content of air exchanging with the continent. Basin-scale ocean flux balances are also critical for placing the North American continent in the Northern Hemisphere context. Quantification of these processes is necessary to understand and interpret the large-scale regional and continental CO_2 flux estimates that will be obtained during the intensive field experiment in 2004–2005. Plans for ocean research to address global issues, summarized in the U.S. Large Scale CO_2 Observation Plan (LSCOP, Bender et al., 2001), and other programs (see Appendix 3) will contribute to the NACP.

Goals of the marine component of the NACP are as follows:

- Provide measurements of air-sea fluxes of CO_2 and carbon burial in coastal waters and adjacent ocean basins
- Elucidate factors controlling the efficiency of the solubility and biological pumps in coastal environments
- Quantify the influence of margin biogeochemical processes on the chemical composition, productivity, pCO_2, burial of organic matter, and deposition/dissolution of $CaCO_3$ in adjacent ocean basins
- Develop coupled physical-biogeochemical models for different types of continental margins.

The NACP ocean carbon component, summarized in Appendix 3, includes both the open ocean domain and the coastal ocean domain; it will coordinate the efforts of ongoing programs into an integrated observing system, and undertake selected efforts not proceeding in other programs.

Open Ocean Domain. Characterization of the air-sea fluxes in oceanic regions bordering North America is critical for isolating processes related to the study region. A long-term basin-scale observation network of underway and time-series measurements, as laid out in the LSCOP (Bender et al., 2001), will provide the measurements necessary to constrain the boundary conditions in the NACP. The NACP portion of the open ocean domain will include expansion of surface ocean transects across the North Atlantic and North Pacific.

One of the objectives of the open ocean domain component of the NACP is to better characterize the spatial and temporal variability of air-sea fluxes in the North Pacific and North Atlantic. Currently we have a reasonably good understanding of the global-scale sources and sinks of CO_2 in the oceans based on the sea-surface pCO_2 climatology developed by Takahashi and coworkers (2001). However, there is still very little information on temporal variations of CO_2 sources and sinks. The open ocean measurements will improve this constraint for the NACP. They will also help place the NACP results in a more global context by monitoring changes in air-sea CO_2 gradients in the remote North Pacific and North Atlantic that correlate with observed seasonal and interannual changes in the net North American uptake.

Coastal Ocean Domain. Continental margins are particularly important for the NACP. Specific objectives of new ocean margins studies are better estimates of air-sea fluxes of CO_2 and carbon burial and export to the open ocean, elucidation of factors controlling the efficiency of the solubility and biological pumps in coastal environments, quantification of the influence of margin biogeochemical processes on the chemical composition of open ocean surface waters, and development of coupled physical-biogeochemical models for different types of continental margins. River-dominated margins and coastal upwelling regions merit special attention due to their dominant role in coastal C budgets (see Appendix 3, Figure A3.1).

The NACP coastal program (Appendix 3) will include (1) long-term observations using coastal transects and buoys with autonomous sensors, and (2) intensive process studies. The long-term observations will be coordinated with aircraft profiles and coastal terrestrial study sites to provide the most complete picture possible at these sites. The long-term sites will also be coordinated with the anticipated location of the process studies to better characterize the dominant controls on the observed CO_2 signals.

Ocean Carbon Modeling. Tracking changes in organic and inorganic carbon pools in coastal and open oceans requires detailed understanding of ecosystem dynamics, interlinking biogeochemical cycles, and oceanic physical circulation. Accurate determination of air-sea CO_2 fluxes requires an understanding of such processes as upwelling, primary production, physical and biological transport, remineralization, and sedimentation. The NACP modeling effort will be designed to assimilate process study information and estimate regional sources and sinks for carbon. Integration of such a wealth of information will be a formidable task, but it is envisioned that developing a cohesive ocean carbon program within the framework of the Carbon Cycle Science Plan will act as a first step in such an effort.

Quantification of coastal and open-ocean carbon fluxes will involve a hierarchical approach, with widely distributed in situ observations, remote sensing, and modeling efforts. The field experiments will provide a foundation for satellite and model-based interpolations of oceanic CO_2 fluxes over a broad range of temporal and spatial scales. The modeling program will be designed to assimilate field results and determine regional CO_2 sources and sinks, providing the data for oceanic CO_2 fluxes required as constraints for determination of continental fluxes.

Data Analysis and Modeling: Data Fusion for Atmospheric, Land Surface, and Ocean Observations

Models and data must be tightly integrated to identify uncertainties and strategies for measurement programs (prognostic models), and to analyze the observations to yield quantitative results and understanding (diagnostic models). Models are the link between processes and observations. They provide a quantitative representation of the physical processes (atmospheric, oceanic) and biological processes (ecological) that together regulate surface fluxes (sources and sinks) and the atmospheric responses to surface fluxes. Thus, model results can be compared to observations of the atmosphere, to satellite data, and to large assemblies of data such as the FIA or land cover maps. Models allow evaluation of the contributions of various mechanisms to the regional flux. Ultimately, predictive models of the future behavior of the carbon cycle will be developed, tested, and improved following systematic comparison to data collected by the NACP and related programs.

The atmospheric measurements collected by the NACP will provide a number of independent means for analyzing the budgets of major carbon gases, divided into two general approaches:

- Tests of predictions from process-based models of carbon sources and sinks, and tests of the algorithms used to extrapolate these models to large scales (“bottom up” analysis)
- Tightly constrained estimates of net carbon flux by mass-balance and inverse modeling techniques, at multiple scales in space and time (“top down” analysis).

Both approaches require that models and data sets for atmospheric transport and for biogeochemical processes be combined and synthesized.

The NACP envisions development and application of a suite of diagnostic models and data assimilation techniques for a range of space and time scales, to obtain improved process understanding and quantitative estimates of carbon flux. A phased approach is planned. Research in data assimilation modeling and numerical experiments to test new concepts occupies the initial phase. Mass-balance and assimilation methods will be employed to estimate regional fluxes during intensive observing periods in the development and testing phase. The required data assimilation system will be built for the installation and operational phase, providing regionally resolved estimates of trace gas fluxes and improved model parameters for prediction of future trends, each with quantified uncertainty.

Most significant sources and sinks of carbon arise from "slow" processes: climate trends, recovery from disturbance and regrowth, the long-term rise in atmospheric CO_2, changes in water tables, nitrogen deposition, and the long-term effects of management (fire suppression, tillage, forestry). However, most of the variance in atmosphere concentrations results from "fast" processes: the diurnal cycle, daily weather, and seasonal variability in climate. This mismatch defines the fundamental problem in defining the long-term budgets of the major C gases. Models used for analysis of data, either top-down or bottom-up, must simulate both fast and slow patterns of variability; measurements and analysis tools must be sufficiently comprehensive and accurate to delineate the long-term trends against the "noise" of fast processes. This is the challenge of the NACP.

The NACP envisions two approaches to this problem: (1) mass-balance and atmospheric data assimilation methods focus on quantifying fast processes (time scales of hours to months), with slow ecosystem changes deduced from residuals versus time-mean behavior; and (2) fully coupled process models allow direct assimilation of both fast and slow processes. Both approaches require substantial investment in improved capability for numerical simulation of atmospheric transport and for evaluation of the transport properties of the models, which are derived from weather forecasting. This investment is the necessary complement to that recommended for the observations.

Forward Simulation of Atmospheric Concentrations

Process models that simulate the carbon balance of terrestrial ecosystems and the ocean mixed layer will be coupled to meteorological models to provide detailed "forecasts" of atmospheric CO_2, CH_4, CO, and other trace gases. The models must be structured to allow direct, detailed comparison with data, thus to identify shortcomings in the simulation of the carbon cycle and the meteorology. High-frequency sampling of the continental atmosphere in the NACP will provide new information on much finer spatial scales than at present, and on diurnal to synoptic time scales. Hence model-data comparisons must represent fast ecophysiological processes and their interaction with atmospheric transport. Correlations (e.g., diurnal) between carbon fluxes and atmospheric transport (the "rectifier effect") remain a major source of uncertainty in global inverse modeling studies. Correct representation of these processes in coupled models is necessary for robust interpretation of global data. Observational tests of these models, including correlations among processes at all time scales, represent a central goal of regional atmospheric sampling and analysis in the NACP.

Evaluation of forward simulations of atmospheric CO_2, CH_4, and CO will make use of both statistical analyses of data from the long-term network and case studies of data collected during intensive observing periods. Statistical studies can often use large-scale transport calculated using winds and sub-grid-scale parameterized mass fluxes produced by Numerical Weather Prediction (NWP) centers (NCEP, ECMWF, NASA/DAO). Global analyses are currently available on grids of 1° x 1° (latitude x longitude) every 6 hours, expected to be 0.5° x 0.5°, or even 0.25° x 0.25° by 2006 (see Appendix 4a on NASA DAO proposed activities). Case studies, especially for intensive operation period (IOP) data from aircraft, may require simulation of small-scale circulation features down to the scale of the PBL, for which mesoscale models will be needed to interpolate to finer resolution at higher temporal frequency (e.g., RAMS, ETA). Accurate trajectories with fine spatial and temporal detail from nested models will also be extremely valuable when using aircraft data from the long-term network to constrain models of carbon and other trace gas fluxes.

Most mesoscale atmospheric models in current use can be run from analyzed meteorological fields at larger scale and are thus already available for use to support field campaigns. Few, if any, are coupled to ecosystem models that predict spatial and temporal variations of photosynthesis and respiration. Intensive field campaigns such as those envisioned for the NACP motivate development of these models, and the results will provide excellent tests. The models will be applied to simulate the coupled interaction of weather, hydrology, and biogeochemistry at scales of 10 km or finer over the whole of North America for periods of up to a year, and at much finer scales for IOPs. These simulations will be evaluated rigorously against data from surface, airborne, and spaceborne platforms, providing new understanding, algorithm development, and code for the coupled global assimilation models envisioned below. *These coupled meteorological-biophysical models should develop in parallel with the observational network for the NACP.*

It is crucial that the full three-dimensional mass fluxes, including those resulting from parameterized (unresolved) processes like cumulus convection and turbulent entrainment, be archived by the NWP centers for use in global and regional transport calculations, and that techniques be developed to ensure that archived analyzed wind fields conserve mass. These issues have been major stumbling blocks for attempts to derive surface fluxes from measurements of atmospheric tracers. A few analyzed fields (NASA DAO) currently include sub-grid-mass fluxes, but most do not. To represent the interaction of diurnal cycles in convection and turbulence with variations in surface fluxes of carbon, energy, and water, models will have to provide fields every 3 hours or less, instead of the current practice of reporting analyses every 6 hours. Additional vertical resolution may be needed near the surface, to capture both ventilation and PBL top entrainment processes. Many model outputs are regridded from dynamic height variables (e.g., sigma coordinates) to conventional coordinates, requiring exquisite attention to conservation of mass in the derived products. These improvements pose major challenges for global models.

Improved inventories of anthropogenic emissions, with higher spatial resolution and tested algorithms for temporal disaggregation (time of day, day of week, season) are needed for the detailed analyses envisioned here (both forward and inverse) (see Appendix 4b). The heterogeneous distribution of fossil fuel sources, with localized emissions in urban areas, leads to significant variance of atmospheric CO_2 concentrations, complicating interpretation of tracer data. CO also has large fossil fuel contributions, and analysis of the CO observations will allow rigorous testing of emission inventories and transport, especially during intensive field studies. Thus, CO serves to distinguish fossil fuel signals from other sources of variance for the major carbon gases, allowing quantification of ecosystem fluxes and other non-fossil influences.

Inverse Modeling and Data Assimilation

Spatial and temporal variations in trace gas concentrations contain information about surface fluxes and the processes that produced them, which can be quantitatively extracted using a family of methods collectively referred to as inverse modeling. Fluxes can be estimated at local to regional scale for short periods by direct mass-balance techniques, in which airborne measurements are used to calculate the time rate of change of concentration in an airmass or the horizontal flux divergence of tracer in a control volume of air. Spatial patterns of concentration can be related to time mean fluxes using methods known as synthesis inversion techniques. Variational data assimilation, Kalman filter, and other estimation methods have been proven for weather analysis and forecasting. These methods allow information to be combined from essentially incomparable data, such as NDVI and wind fields, or high-frequency variations in trace gas concentrations and long-term observations. They provide formal mechanisms to merge disparate data streams (e.g., from flux towers, daily aircraft ascents, satellite imagery) to estimate model parameters.

Mass Balance Methods. The most direct approach to estimating carbon fluxes is by balancing mass flows for either a fixed volume of air (Eulerian frame) or a volume of air that follows the atmospheric flow (Lagrangian frame), both of which will be used to prepare for data assimilation at a later stage. Lagrangian approaches are best suited for intensive campaigns, especially in regional experiments, where aircraft flights sample the same airmass at multiple times. This approach has been developed and successfully applied in the COBRA regional experiments (Gerbig et al., 2001, Lin et al., 2001). The method provides a direct and precise measurement of surface fluxes at regional scale, as it eliminates horizontal advection terms present in budgets conducted in a non-airmass-following framework. Eulerian approaches are more readily applied to estimate fluxes over North America from the long-term network, with many observation points distributed discretely across the continent.

Synthesis Inversion. Estimates of surface CO_2 fluxes from atmospheric concentrations by "synthesis inversion" are typically completed in two steps. In the first step, forward simulations are carried out for prescribed surface sources and sinks over large regions (e.g., temperate North America in July). In the second (inverse) step, the magnitudes of unknown surface fluxes are estimated by fitting the forward predictions to atmospheric observations. Variations in the prescribed fluxes within the large regions must be specified from prior knowledge (e.g., fossil fuel combustion patterns and satellite vegetation imagery), due to the sparse observations available. An analogous procedure may be carried out using a time-reversed Lagrangian approach, where winds are run backward (an adjoint model) and the influence of ground sources is estimated. These techniques allow the quantitative insertion of data from other sources (e.g., emission inventories, satellite vegetation data) and their uncertainties, and produce final uncertainty bounds along with flux estimates.

Variational and Kalman Filter Methods. Variational and Kalman filter assimilation methods use estimation theory to optimize a set of parameters to time-varying data, minimizing a cost function whose derivatives relative to observed quantities are known. These techniques form the basis of modern weather analysis and forecasting, and allow maximum flexibility with respect to the temporal and spatial filtering of the observations. Thus, high-time-frequency variations in concentration (e.g., that result from passing synoptic weather disturbances) can add large amounts of information to the flux estimation, rather than being treated as "noise."

The wealth of observations envisioned from the NACP will provide much tighter constraints on inverse calculations than have been possible previously. Given a complete archive of both resolved and unresolved transport, the generation of the adjoint of a transport model is straightforward. This approach estimates fluxes at the resolution of the gridded meteorological analysis, which are then aggregated to coarser scales according to the degree of data constraint available. Systematic, regionally coherent offsets between forward and inverse results will allow testing key ideas about factors that underlie slowly varying ecological processes, such as forest regrowth and woody encroachment.

The NACP will initiate the development of formal data assimilation methods to use comprehensive observations relevant to CO_2, CH_4, and CO. Data will cover atmospheric composition from flask collections, tall towers and buoys with continuous samplers, instrumented aircraft with continuous profiles, upward-looking spectrometers measuring column amounts, and satellites with global coverage. Measurements from satellites and at the surface will provide data on the state of soils, vegetation (including biomass), and ocean biota. Surface fluxes will be measured at instrumented towers by eddy covariance. Inventories will define changes in biomass, agricultural productivity, and soil carbon over long time scales. Buoys, moorings and ships at sea will define air-sea fluxes.

Simple process-based descriptions of photosynthesis, ecosystem respiration (or methanogenesis, for CH_4), growth, and air-sea gas exchange will be coupled to the atmospheric transport model, and the adjoint of the coupled model developed. A generalized cost function will then be minimized, allowing estimation of key parameters in the carbon process models, rather than area-averaged surface fluxes as for synthesis inversion. The system provides best-fit values for parameters in the underlying biophysical models that describe processes responsible for the fluxes, such as temperature-moisture sensitivity of soil respiration, wind-speed dependence of the air-sea gas exchange coefficient, photosynthetic capacity of forest canopies, and seasonal or annual imbalances in mass flows to longer lived pools of organic matter. In this way, assimilation into global coupled models not only provides time-resolved maps of surface carbon exchange, but also leads to progressive improvement in the predictive capability of the process models. This approach has already been demonstrated using simple atmosphere–land biosphere models (Wang and Barrett, 2001; Rayner et al., 2001), which show quantitative uncertainty reduction for estimates of both regional flux and model parameters.

A fully coupled variational data assimilation system that combines meteorological analyses with carbon cycle process models, simultaneously constrained by meteorological as well as carbon data, is a long-range goal of the NACP. That effort will require participation by one or more operational NWP centers, because substantial computational, data-handling, and human resources are required. Real-time and reanalysis products will both be needed because some observations (e.g., flask sample analyses, satellite data on state of the vegetation) take weeks to obtain.

Assimilation of atmospheric CO_2, CH_4, and CO data and spaceborne data directly into the analysis of an operational numerical weather forecast model would be an optimal way to perform the data assimilation task envisioned as a long-term goal. Tracer concentrations carried as prognostic variables in the assimilation provide strong constraints from the "memory" in the atmosphere and reduce artificial noise from poorly constrained satellite retrievals. Assimilated concentrations of CO_2 and other tracers in operational NWP models would produce fully populated, global gridded data, filling the gaps left by clouds, yet remaining optimally consistent with existing observations. The underlying source fields, derived by the models to be consistent with observations, provide estimates of emission or uptake rates gases.

Coupled meteorological, biogeochemical, and trace gas data assimilation will contribute better weather forecasts and climate models. Comparison of simulated trace gas data with observations will help expose model flaws. Knowledge of atmospheric CO_2 concentrations has recently been shown to improve the retrieval of temperature profiles from infrared spectroscopy, reducing forecast initialization error by as much as 1°K over some regions (Engelen et al., 2001).

This program is technically feasible. Implementation could start as early as 2002, when CO_2 estimates begin to be available from the Atmospheric Infrared Sounder (AIRS) aboard EOS-Aqua. Indeed, ECMWF has already begun such a development effort, with the aim of real-time assimilation of both atmospheric CO_2 and its surface sources and sinks within three years. NASA DAO may pursue a similar effort. New resources would be required, with potentially large scientific return, especially later in the decade when higher quality global satellite products are expected. A workshop involving operational weather centers and carbon modelers is planned to examine performance and resource requirements, and to begin work on an implementation plan.

An important function for early versions of coupled models is analysis of bias in trace gas data from satellite retrievals, requiring substantial field sampling programs and sophisticated methods for comparing in situ and remote-sensing data from the sustained and intensive campaigns (elements 1a and 1b). We will be able to determine bias associated with sensors relying on reflected sunlight, which see only daytime conditions and thus have systematically lower CO_2 concentrations over vegetated land than the true mean. Similarly, spaceborne observations of CO_2 concentration will be biased to clear sky conditions.

A study to design the NACP long-term observational network is one of the highest priorities for initial model development. Previous atmospheric and biospheric data and the atmospheric reanalysis data (see Appendix 4a) can be used with the new models to assess network designs, intensive campaigns, and other NACP concepts before implementation. A first step in this effort is a modeling study/workshop focusing on network design scheduled for summer 2002.

By the end of the decade, the goal should be an assimilation system that includes a model treating the fluid dynamics and physics of the atmosphere and oceans and the biology and biogeochemistry embedded in each. This coupled model would predict many quantities that are directly observable (including temperatures, winds, and radiances at the top of the atmosphere that result from radiative interactions with vegetation, phytoplankton, and atmospheric trace gases such as CO_2 and CO). The system would then minimize a generalized cost function that includes deviations of each of the predicted quantities from the observations, to include observations at the surface, by automated in situ sensors, and from space, enabling near-real-time analysis of the elements of the carbon cycle on land and in the oceans, and of the processes that give rise to sources and sinks.

This new data fusion system will be invaluable for monitoring present conditions and for learning about the coupled Earth system. Most important, it would enable development of falsifiable predictive models for future behavior of the carbon cycle and the climate system. This is a very ambitious program that calls for substantial effort in computational and human resources, requiring significant resources in advance of the actual field observations.

Summary

Goals for atmospheric modeling and data assimilation support for the North American Carbon Program are the following developments:

- Simulations of the major elements of the NACP in forward runs of coupled models to help guide design of the networks and IOPs (Phase 1)
- Fully coupled forward process-based simulations of surface carbon exchange processes and trace gas concentrations on a 10 km grid for the experimental

domain for one year, to be evaluated with data collected during the Phase 1 experiments (modeling in Phase 2)

- High-resolution weather forecasts for targeted areas during IOPs, to aid in flight planning and data analysis (modeling in Phase 2)
- Fine-scale (cloud-resolving) simulations of the IOPs with fully coupled process-based models (Phase 2)
- Estimates of regional fluxes of CO_2, CO, and CH_4 during IOPs using Eulerian and Lagrangian mass balance methods (Phases 2 and 3)
- Production of archived global transport fields from at least one operational analysis center (ECMWF, DAO, NCEP) on a 50 km grid, including both winds and parameterized vertical mass fluxes, on a time step of one to three hours (Phases 2 and 3)
- Assimilation of tracer concentration from flask samples, continuous analyzers, tall towers, airborne measurements, and satellite products into the global archived transport field, to produce global 4D grids of CO_2 and CO and isotopic ratios of CO_2, and surface fluxes consistent with them
- A coupled carbon cycle and meteorological data assimilation system, in cooperation with one or more operational NWP centers, for optimization of both fluxes and process parameters (Phase 3).

Chapter 3: Synergy

Synergy of the NACP with Other Major Areas of Research

Atmospheric Chemistry

The intensive field programs and long-term measurements of the NACP offer unique opportunities for joint research with atmospheric chemistry programs at NASA, NSF, NOAA, and DOE. Trans-oceanic and trans-continental transport and transformation of pollutants are among the most important issues of current interest in atmospheric chemistry. Major airborne field programs are currently under discussion for North America in the time frame being considered for NACP IOPs. The synergy between the NACP and atmospheric chemistry programs is evidently bi-directional, with potent benefits flowing in both directions.

Intensive Field Campaigns with Atmospheric Chemistry

Consideration of potential experiments suggests that joint missions between the NACP and atmospheric chemistry programs would offer major advantages, providing enriched data sets with very few tradeoffs. The NACP focus on long-lived tracers, exchange processes between the PBL and the free troposphere, and partitioning of sources and sinks between forests, agriculture, and industry, provides key information for studies of pollutants that travel long distances in the atmosphere. The enormously sophisticated instrument payloads for chemical measurements on heavy-lift payloads (DC-8, C-130, P-3) provide extremely powerful multi-tracer constraints for source/sink attribution, as well as data to help define the magnitude of complications such as in situ production of CO from labile hydrocarbons or long-range transport of concentration anomalies for CO_2, CH_4, or CO in the upper troposphere.

The NACP plan therefore envisions that the intensives will be carried out in close collaboration with atmospheric chemistry programs and the associated airborne measurement missions.

Long-Term Airborne and Surface Measurements with Atmospheric Chemistry

The NACP plan calls for frequent (1 to 2 day interval), continuing measurements of atmospheric composition using a limited number (2-4) of small jet aircraft, intended to provide critical complements to the soundings by light aircraft. These jet aircraft platforms will transit coastal regions, higher altitudes, and other areas inaccessible to light aircraft. Their payloads can potentially include a wide range of chemistry measurements, including radicals (NO_X, possibly OH), nonmethane hydrocarbons, aerosol composition, and others. A number of possibilities have been discussed for developing small, rugged sensors that could be used for this type of work, and development activities are under way.

Data provided by these aircraft will not only aid the NACP, but could revolutionize understanding of atmospheric chemistry over North America. Currently, data are collected routinely mainly at sites in polluted areas, and aircraft data are limited to a rather small number of campaign-style missions, also usually in polluted areas. The new data will provide insight into background conditions and long-range transport not hitherto available.

Measurements of reactive chemicals and aerosols at ground stations provide complementarity and will be undertaken at a similarly selected, limited subset of the ground stations (tall towers and flux towers).

The NACP plan envisions a small number of jet aircraft in the long-term measurement program operated jointly with atmospheric chemistry programs and equipped with sensors for key reactive species and aerosols.

Resource Management and Ecological Sciences

The NACP has strong synergy with resource management (forests, agriculture) and ecological research programs, primarily in two ways. The benefits are evidently bi-directional, as for chemistry.

Long-Term Measurements and Emergent Properties of Ecosystems

The carbon budget of a region represents an integral emergent property of the ecosystems there on a large scale. For land managers, this means, for example, that the actual accumulation of fuel on fire-prone lands can be measured. The carbon budget for the growing season in the Corn Belt tells managers in near-real-time the growth trajectory of the crop, complementing conventional measures such as NDVI.

Transient Responses to Environmental Forcing

Seasonally resolved rates for net uptake or release of CO_2 from agricultural and forest ecosystems provide unique, quantitative indicators for processes and net productivity at the landscape scale. NACP measurements in the long-term network and IOPs, and calibrated, near-real-time ecosystem models for vegetation will measure the effects of climatic variations on ecosystem net growth with time resolution sufficient to resolve major shifts as they are occurring.

The NACP plan envisions close coordination between carbon cycle science and resource management and ecological programs, with joint consideration of measurement and modeling issues to maximize two-way synergy.

Weather Forecasting and Climate

There is a critical synergy between NACP efforts and weather and climate studies. Flux tower data and biophysical model analyses, available in near-real-time, provide improved constraints on latent and sensible heat fluxes, roughness lengths, and other properties. Currently, surface flux data have no direct impact on weather forecasts, because the data are not available for assimilation, and assimilation frameworks do not exist. The development of these data sets and associated diagnostic models incorporating remotely sensed forcings promises significant benefits for weather forecasting.

The potential for CO_2 concentrations and fluxes to benefit meteorological forecasts and analysis has been recognized at the ECMWF, which already has research under way to enable simulation of CO_2 distributions in the atmosphere; once the data are available, forecasts will use variations to correct satellite-derived temperatures. More sophisticated applications are also envisioned. Tracer distributions are very sensitive to the details of atmospheric advection, and assimilation of tracer observations could help improve forecasts by improving representation of boundary-layer processes. ECMWF has in place plans to assimilate CO_2 data with this objective in mind. Additional synergies involving, for example, CO data deserve exploration.

The program envisions close collaboration with operational centers to enable NACP tracer data to be utilized to improve operational weather forecasting. Parallel applications to help improve climate models are a high priority for developments in surface-atmosphere models for CO_2 sources and sinks.

Chapter 4: Management and Deliverables

Management of the NACP

The North American Carbon Plan represents a scientific agenda that is unprecedented in the history of carbon cycle research in the United States. The integrated nature of the carbon cycle and its inextricable connection to human activities make it one of the most complex Earth science topic areas at the present time. These facts, combined with the urgent need for policy-related information on controls on greenhouse gases in the atmosphere and how they will evolve in the future demand innovative management of the scientific enterprise and timely communication of results.

The U.S. portfolio of carbon cycle research is very diverse and is funded through diverse mechanisms for disciplinary scientific research and specific agency missions. Implementation of an integrated program as envisioned for the NACP requires strong coordination, both at a scientific level and at a funding agency level. The healthy diversity of the federal research enterprise should be harnessed by providing incentives and mechanisms for ensuring that research under the NACP is closely managed to achieve its objectives.

Guiding principles for integrated federal support for the NACP include adherence by agencies to a single scientific planning process and unified scientific guidance of the integrated program. To ensure that implementation stays current with scientific results, a single scientific steering group should guide implementation so that the distributed parts of the enterprise are meeting common goals. And, finally, a single international interface should be encouraged so that national efforts can work efficiently with efforts in other countries to achieve a globally consistent view. The practical implications of these principles include supporting a functioning process for close, interagency collaboration, developing common processes for project solicitation and review where applicable, and subscribing to a collaborative interagency process for making funding decisions.

The federal research system is not inherently predisposed toward this mode of operation. If an integrated research program is truly to be effective, strong incentives at top levels of agency management, including OMB, must be in place. Opportunities for coordinated budget initiatives across agencies must be supported. Progress towards goals should be reviewed at a cross-agency, integrated level. An integrated research program can deliver products such as described in the NACP, but only if the will exists to embark on an experiment in creative management of a diverse research enterprise.

Deliverables of the NACP

Overarching deliverables of the NACP are the following:

1. Measurements of sources and sinks for CO_2, CH_4, and CO for North America, at scales from continental (5,000 km) to local (10 km), with seasonal resolution.
2. Attribution of the sources and sinks to the full suite of contributing mechanisms, including climate change, atmospheric change, and land use history.
3. Documentation of North America's contribution to the Northern Hemisphere carbon sink, placed in the global context.
4. Documentation of the effects of land management and land use history on carbon balances.
5. Process understanding necessary to improve future predictions and management of the carbon budget for North America
6. Optimized sampling networks (both ground-based and remote) to determine past, current, and future sources and sinks of CO_2, CH_4, and CO.
7. Data assimilation models to compute carbon balances.
8. *State of the Carbon Cycle for North America*, a periodic report communicating results to the public.
9. Data and observations to provide the foundation for major advances in atmospheric chemistry (better determination of sources and transformation of pollutants), resource management (improved knowledge of ecosystem function and response to global changes), and weather forecasting and climate models (real-time tracer concentration and flux data, coupled models with greatly improved representations of atmosphere-biosphere coupling, surface energy and mass fluxes).

Appendices

Appendix 1

Initial Concepts for Atmospheric Observations

Phased Build-Up of the Long-Term Observing System

Current plans for the long-term observing network envision three phases, to be modified and optimized with the aid of model studies and initial data.

Phase 1 (Summer 2004): Preliminary Work

The initial implementation phase will focus on the agricultural area of the upper U.S. Mid-West, centered on the state of Iowa. This area has high agricultural productivity, low population density, and flat terrain. The expected CO_2 signals will be sufficiently large, and the dominating CO_2 sink due to crops can be estimated independently, allowing for a proof of concept. The expected differences in CO_2 across Iowa can be estimated: with a diurnally averaged net sink prior to harvest of 5 mol C m^{-2} s^{-1} (from corn and soybeans, 60% of all state land is devoted to these crops), the average CO_2 decrease over one day, if confined to the lowest 2 km of the atmosphere, would be about 5 ppm. This is the expected difference across the state, since at an average wind speed in the boundary layer of 5 m/s, the signal has about a day to build up over Iowa (about 400 x 350 km). This is a sufficiently large signal to test the method.

The problem we want to address eventually has a much smaller signal, however. If through optimized soil management the United States could store as much as 0.2 Pg C/year as organic carbon in agricultural land, and if we apportion 8% of that to Iowa (its share of the total U.S. market value of agricultural products), the annually averaged rate of C storage would be 0.3 mol C m^{-2} s^{-1}, approximately equal to the emission of CO_2 from Iowa from combustion of fossil fuels. This estimate suggests that it may be possible to verify this type of carbon storage on agricultural land, but the region must be several times the area of Iowa to obtain a larger average drawdown for CO_2.

A relatively large number of very tall transmitter towers are located throughout the Midwest and Southeast United States (especially the Carolinas). We plan to instrument five tall towers in the Iowa study area, one centrally located and four surrounding it at distances of 300 to 800 km (Figure A1.1). In addition, there are the existing tall tower sites in northern Wisconsin (500 km to NE), and central Texas (1,200 km to S). The central Iowa tower (near Des Moines) should measure fluxes as well as concentrations. New aircraft profiles would be established over three of the new towers as well as the existing Wisconsin and Texas towers. Aircraft profiles would be obtained every 2 days at each of these sites and at the existing aircraft sites in Colorado and over Harvard Forest, Massachusetts.

Note that requirements for measuring net fluxes of CH_4 and CO are less stringent in general than for CO_2, since fluxes of these gases from the surface do not reverse sign seasonally or diurnally.

In addition to the intensive study area, a few dispersed observing stations should be added across the continent and around its perimeter during the early phases of network development. For example, some of the existing AmeriFlux towers could be instrumented with accurate CO_2 measurements and extrapolations could be made to mid-PBL mixing ratios from the surface layer flux and mixing ratio data. One or two measurement sites should target an area of hilly terrain to make an exploratory effort toward atmospheric measurements in these areas, which would also be a focus area during the early intensives. Also, CO_2 measurements on a few permanently moored buoys ˜50 km from the shore should be initiated (see Appendix 3). These relatively inexpensive enhancements to the network would provide a larger scale view of CO_2 distribution over the continent and would be important data for modeling studies of network design.

Phase 2 (Fall 2004): Intensive Field Studies

As we expand the long-term network in the central part of the country, we will start to encounter large fossil fuel sources. We envision at least one intensive during this expansion phase to help establish the capability of the experimental design to distinguish urban/industrial emissions from distributed sources and sinks associated with vegetation and soil processes.

Phase 3 (Summer 2005 and Beyond): Build-Out of the Network

To improve the capability for establishing a continental mass balance there should be a ring of stations along the coasts, in northern Canada, and along the southern U.S. border. With spacing of ˜1,000 km, there will be about 12

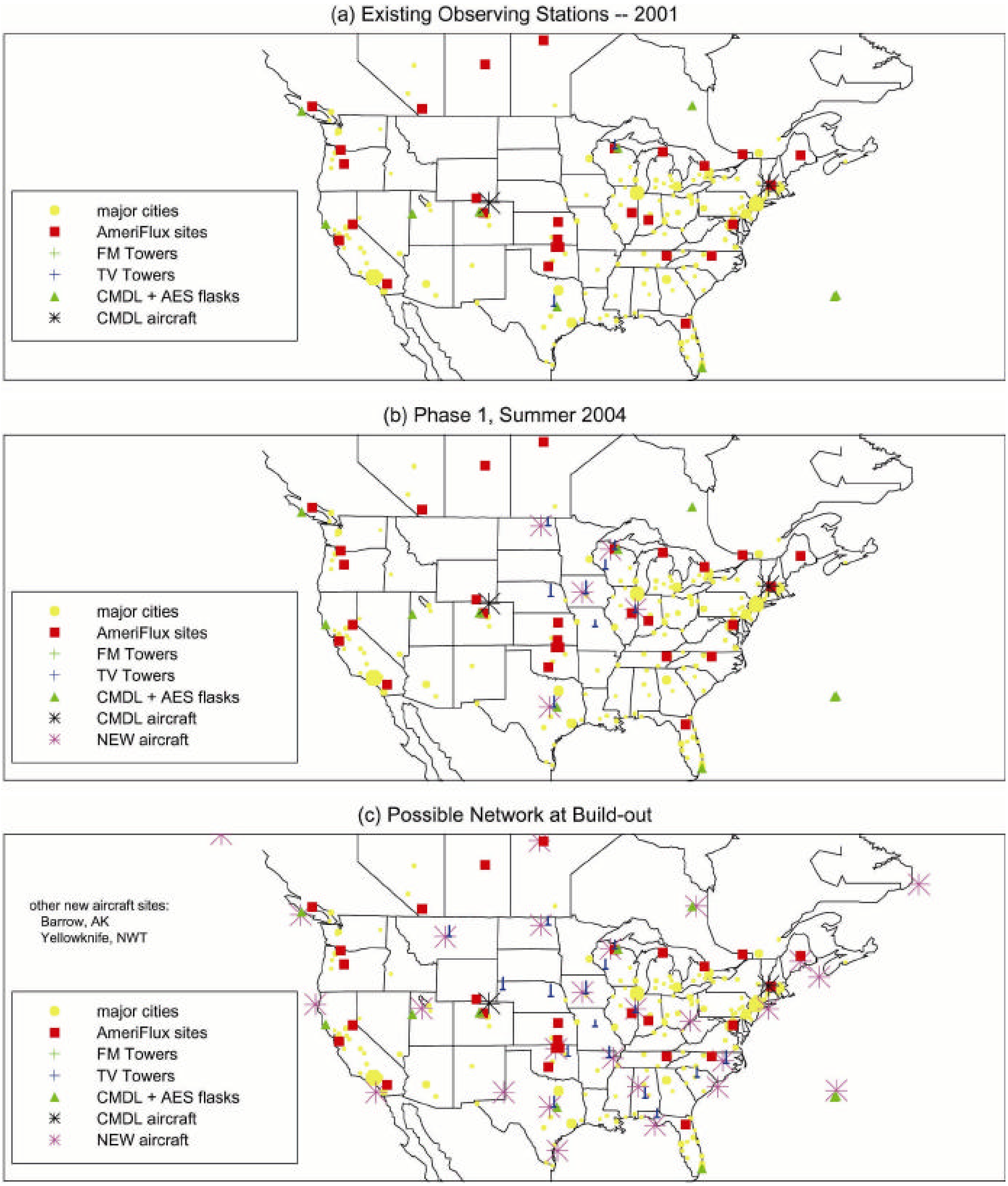

Figure A1.1. Evolutionary design for the NACP atmospheric observation network. Note: Final buildout of the Ameriflux network is not represented pictorially. The location of additional sites will be determined in conjunction with the execution of field campaigns.

stations in the ring and perhaps 18 inside, in a more or less regular grid east of the Rocky Mountains.

Figure A1.1 shows maps with (a) locations of existing observing stations, including flask sites operated by NOAA/Climate Monitoring and Diagnostics Laboratory (CMDL) and the Atmospheric Environment Service (AES) of Canada, AmeriFlux sites, and current aircraft sites operated by NOAA/CMDL; (b) phase 1 proposed enhancement of the long-term observing network, adding several tall tower and aircraft profile sites focused in the agricultural belt around Iowa; and (c) a possible full observing network for North America at build-out, including a total of 30 aircraft sites and 15 tall tower sites. (Cities with population over 300,000 are shown with symbol size proportional to population.) Coastal aircraft flights will be over permanent buoys moored offshore, improved from existing instrumentation to provide accurate atmospheric data traceable to international standards. AmeriFlux sites currently measure fluxes, but none provide atmospheric concentration data certified traceable to international standards. Some AmeriFlux sites will be enhanced for accurate measurements of CO_2, CH_4, and CO mixing ratios and real-time reporting of data.

A few AmeriFlux and other sites will also have column integral measurements using Fourier transform infrared absorption spectrometers to characterize the diurnal cycle and measure the daytime uptake under cloud-free or partly cloudy conditions. Hilly terrain will be addressed with some sites and targeted during the intensive campaigns to develop appropriate sampling methods in these complex areas, and to aid in development of transport models. We envision that full deployment of the network may take several years. Its design will be refined when the data from the intensives in 2005 and the results from at least a full year of sustained observations have been digested and models improved.

Quality Control of the Observations. The information we seek to extract is contained in small concentration differences. It is paramount that all data are directly comparable to a high level of accuracy (e.g., 0.2 ppm for CO_2). Well-defined instrument calibration protocols will be followed on all flights, including the intensives, and at the ground stations. All CO_2 and CO measurements will be made on the respective WMO mole fraction scales, maintained by the NOAA CMDL, and CH_4 on the CMDL scale. However, experience has shown that careful calibration is not enough. There can be problems with gas handling independent of the calibration. All in situ measurements of CO_2, CO, and CH_4 will be compared to regular (dried) whole air samples in flasks measured in one laboratory. Flask samples will be obtained on a subset of the flights for the sustained observing system, every 10 days or so, once a day in mid-afternoon (when the boundary layer is maximally mixed) on the tall towers, and perhaps one flask per hour per airplane during the intensives. When the flask results differ from in situ measurements, this needs to be investigated immediately. The problem could be with either method. Rapid turnaround (of a few days) of flask samples is essential so that sampling problems do not persist. Sampling with flasks has the further benefit that additional species and isotopic ratios can be measured.

Data management. All data will be made generally available immediately in preliminary form at a single website. Rapid comparison of different data sets is essential for maintaining quality control. Data will be “flagged” and corrections made as the analysis proceeds.

Intensive Operation Periods (IOPs)

Phase 1 (July 2004): Exploratory Measurements

The first phase will focus on defining distributions of target gases across the continent, and on smaller scale experiments in a selected region where the first stations of the long-term network have been started. Emphasis will be given to testing the integrity of the measurements and analytical concepts.

Large-Scale Distributions. Observed atmospheric concentrations and linkage to vegetation and atmospheric chemistry will be stressed. Large-scale measurements are expected to link up with airborne observations from coordinated atmospheric chemistry missions such as NASA's Global Tropospheric Experiment and NOAA experiments.

Small-Scale Experiments. Data will be collected over a major agricultural region (e.g., Iowa, or the Mid-West corn belt) using regional budget experiments and frequent vertical profiles over tower locations, providing tracer distributions with much higher spatial and temporal coverage than the network. Budget estimates from regional inversions will be evaluated by comparing results from the network stations and the intensive aircraft data, and further compared to independent bottom-up flux estimates, based on agricultural productivity. Additional intensive study may focus on hilly or complex terrain. The intensives will rigorously test the integrity of network design, the analysis tools, and specific issues such as complex terrain.

Phase 2 (Nov. 2004–Jan. 2005): Development Period

Measurements will emphasize determination of emissions from a major source region reasonably separated from other sources (e.g., an urban complex such as Minneapolis/St. Paul). A different season from that of phase 1 will be chosen, and a comprehensive set of large-scale observations will be obtained again, providing a look at cross-continental gradients in fall. The goals are to refine the overall approach, and to gain data characterizing regions where the long-term network is expanding.

An urban complex will be studied in a regional budget experiment in which we will characterize urban emissions of CO_2, CO, and CH_4 from a fairly isolated metropolitan complex in flat terrain. These observations will provide the tracer-to-tracer ratios characteristic of the urban plume. Urban emissions will be separated from fluxes due to vegetation and soils, which are still significant in the fall, but not dominant as during the summer. Data assimilation with high spatial and temporal resolution requires knowledge of the fossil fuel source of CO_2 on small temporal and spatial scales. Intensive regional measurements around an urban complex serve as test bed for analyses of this problem.

Candidate Site: Minneapolis/St.Paul, Fall 2004

There are a number of towers taller than 300 m in the vicinity of Minneapolis/St. Paul. Three are within 15 km of the center, with one at 50 km S, one at 40 km N, one at 40 km W, and seven more between 100 km and 200 km distance. We would instrument at least one tower at 40-50 km distance, and one due east at 100 km. Regular vertical profiles will be flown over the latter and a spectrometer installed.

Large-Scale Cross-Continental Gradients. It is important to determine if the network can distinguish CO_2 gradients imposed by global processes from sources (decay) in the dormant season, and separate biogenic from anthropogenic CH_4. Since sources of CO from biomass fires and photochemistry are relatively small at this season, the measurements will provide a quantitative test for emissions inventories for CO.

Phase 3 and Beyond

The program envisions additional intensive studies, covering at least the seasons not previously sampled, winter and spring. In winter, fossil fuel sources should dominate biological sources and sinks for CO_2, CH_4, and CO, allowing strong tests of emission inventories. However, both the network and the intensives will face operational difficulties due to weather, and the intensive phase will emphasize large-scale observations to test the capability of the network. In spring there are strong soil sources of CO_2, but the observations will be complicated by strong geographical gradients, with growth of plants commencing in some areas while in others plants are mostly dormant.

Intensive Field Campaigns

Possible Aircraft and Instruments in the Intensive Field Missions. The atmospheric aircraft platforms for NACP field programs emphasize remote sensing:

- **Atmospheric data.** Principal species: CO_2 (+/-0.2 ppm), CO (+/-1 ppb), CH_4 (+/- 5 ppb), and H_2O.
- **ER-2.** An airborne simulator for future satellite measurements of biomass and atmospheric CO_2, CO, and CH_4 profiles. Tests will include direct comparison with data on the ground and from the in situ aircraft listed below, plus AVIRIS and other remote-sensing instruments for vegetation cover, canopy chemistry, and biophysical parameters.
- **Citation aircraft.** Lagrangian, survey, and boundary-layer flights. Limited payload includes in situ measurements of CO_2, H_2O, CO, and meteorological parameters, possibly O_3.
- **5-10 light aircraft**. To be used in phase 1 of the long-term network: fixed-point vertical profiles daily (continuous for CO_2, CH_4, CO, possibly O_3) twice per day, alternate days, over continental sites and over marine (CMDL) stations, using the new instrumentation developed for the long-term network.

The NACP IOPs will be combined with atmospheric chemistry programs to obtain additional heavy-lift, long-range platforms for continental-scale measurements. Three likely candidates are the following:

- **DC-8.** Large-area surveys, including high altitudes and all along the coasts and borders to define boundary values for the United States and adjacent areas of North America. Instrumentation would include in situ measurements of CO_2, H_2O, CO, and O_2, with a full complement of atmospheric chemistry measurements (free radicals, solar radiation, nitrogen oxides, etc). The mission profile would include observations for NACP purposes as part of a major deployment for studying the chemistry and transport of pollutants over North America.

- **P-3.** Eddy flux flights and smaller-area flights, including boundary layer, possibly also in conjunction with atmospheric chemistry payloads and mission profiles.
- **C-130.** Similar to Citation or P-3, with full chemistry and/or remote sensing.

*INTEX-NA and the NACP First Intensive Measurement Periods***.** The first opportunity for joint NACP–atmospheric chemistry measurements will be in the Intercontinental Transport Experiment–North America (INTEX-NA) program in 2004. INTEX-NA is a NASA Global Tropospheric Experiment (GTE) aircraft mission focused on quantifying the sources, sinks, and import/export of environmentally important chemicals on the scale of the continental United States. Chemicals of interest include ozone and its precursors, aerosols and their precursors, and long-lived greenhouse gases. INTEX-NA will use two NASA aircraft, the DC-8 (ceiling 12 km) and the P-3B (ceiling 7 km) operating along the Atlantic and Pacific seaboards as well as over the continental United States. Two deployments are planned, in summer 2004 (Phase A) and spring 2006 (Phase B). Sampling strategies will be guided by information from satellite observations and atmospheric models. Coordination will be sought with NACP and with other experimental programs focused on U.S. air quality (NOAA, DOE), and transatlantic transport (EEC). Validation of Aura satellite observations and scientific application of these observations to address mission objectives will represent an important component of the INTEX-NA activity.

INTEX-NA will follow an experimental design in which bottom-up, prior knowledge of chemical sources and sinks on the scale of the United States can be tested and improved in a top-down manner with atmospheric observations. This design requires an integrated approach where synthesis of the aircraft observations with measurements from other platforms (satellites, sondes, surface sites) and 3-D atmospheric chemistry models is pursued at all stages of mission design, execution, and interpretation. The aircraft flights will be directed at optimal sampling of the continental boundary layer (CBL), of the exchange between the CBL and the free troposphere (FT), and of the synoptic-scale flow across the coastlines and over the neighboring oceans. The aircraft will carry high-performance instrumentation for measuring a wide range of chemical species, building on the capabilities developed for previous GTE missions. These include (1) extensive in situ measurements, (2) eddy correlation flux measurements from the P-3B aircraft, (3) remote-sensing (DIAL) measurements of ozone and aerosols aboard the DC-8 aircraft. The optimal sampling strategy to enable top-down analysis will be developed prior to the mission using atmospheric model simulations and prior observational knowledge. It will be implemented during mission execution through the use of 3-D model forecasts and satellite observations, and through coordination with other field programs including NACP.

Phase A of INTEX-NA will prioritize the eastern United States and outflow to the North Atlantic. Phase B will emphasize inflow from the Pacific. However, both phases will extend their scope to the continental scale. Sampling with the DC-8 will focus on the Atlantic and Pacific seaboards to characterize continental-scale inflow/outflow, and will include transcontinental transects aimed at quantifying large-scale chemical gradients over the United States as well as transport involving Canada and Mexico. Bangor and Seattle are planned as the principal operational bases of the DC-8. The P-3B will focus on regional-scale mapping of surface fluxes and characterization of CBL-FT exchange over the United States. It will be based at interior sites in the country; a site in Wisconsin is presently under consideration. The deployment of the P-3B will be conducted with deliberate intent to maximize opportunities for collaboration with NACP and other field programs towards addressing the INTEX-NA mission objectives.

Close coordination between INTEX-NA and NACP is indeed a compelling investment to augment the scientific returns of both programs. A common objective is the characterization of carbon sources and sinks over the United States. The NACP measurement platforms and biogeochemical modeling resources will be of considerable value for INTEX-NA. The extensive chemical tracer observations together with CO_2 and methane available from the INTEX-NA aircraft will offer powerful constraints for carbon sources and sinks. The eddy correlation flux measurements and vertical sounding capabilities of the NASA P-3B aircraft will complement the smaller-scale mapping by the NACP aircraft, while the continental-scale observations from the DC-8 will allow an integrated perspective on carbon budgets. Such fruitful coordination between INTEX-NA and NACP needs to be pursued actively at the mission planning stage to lay the groundwork for successful execution.

Appendix 2

Phased Implementation of Biophysical/ Biogeochemical Measurements and Models

There are three broad, consecutive phases in implementing the biophysical measurements and modeling part of this program, corresponding to the phased approach described in the section on atmospheric measurements: (1) preliminary work, (2) intensive field studies, and (3) long-term implementation. Preliminary work is to be completed prior to initiation of this program using existing funding mechanisms.

Phase 1: Preliminary Work

Enhancements to Intensive Networks, Extensive Inventories, and Land Cover Data

The existing extensive AmeriFlux network and extensive inventories have gaps in geographic coverage and methodologies that can potentially be addressed to provide complete coverage of the land surface. Identified gaps include developed lands (urban and suburban), rangelands, pinyon-juniper forests, and interior Alaska. *Preliminary work should include systematically defining how networks and inventories should be upgraded, and developing a strategic plan to accomplish this goal.*

A prototype database of historical information should be developed in the preliminary phase, including the current state of land surface (cover, age since disturbance, type of disturbance, management, biomass, soil carbon stocks). LandSat data collected over the continent during the 1980s, 1990s, and 2000 and 2002 (in preparation for campaigns beginning in 2004) need to be assembled and processed to provide high spatial resolution land cover change information for the last two decades.

Measurement Issues for Intensive Networks and Field Campaigns

With regard to field tests and deployment of new instruments: New methodology for in situ soil C measurements is becoming available. They must be tested, and if suitable, used for more background and benchmark validation measurements. Only a few AmeriFlux sites carry out required biophysical measurements and have the instruments, on-site data processing, and communications required to supply the data at appropriate time scales to integrate with the atmospheric studies. We need to augment capabilities to allow the measurement of all C gas fluxes and to partition the component fluxes at resolutions that will allow the quantification of daily, seasonal, and interannual variability at appropriate spatial scales. New low-power, high-precision, high-frequency detectors for CO_2 (NDIR), and CH_4 and CO (GC or NDIR-gfc) need to be developed and deployed as part of a low-cost chemistry/meteorology package to expand measurement capability. Related to all proposed measurements, standards need to be developed to prepare for future implementation. *Preliminary work should involve instrument development, upgrading of a limited number of sites, and developing and implementing pilot studies of data communication and data fusion.*

Model Development and Applications

Analysis needs should be identified early in the program so that model development may provide appropriate information. Input and output variables needed by a variety of models need to be specified. Model comparison studies may be useful. Testing of methods to integrate new measurement protocols with existing intensive and extensive sampling networks is an ongoing activity. Activities for the preliminary phase include developing an understanding of model functionality, including operational input and output specification. *Pilot development of actual working models should be undertaken, linked to the pilot work on enhanced intensive sites and inventories.*

Evaluation of Information Capabilities of New Remote Sensors

Some remote sensors have been in use long enough that their capabilities are well known (e.g. LandSat-TM). Others, such as EOS-MODIS, are relatively new and evaluation studies are underway. In addition, above-ground biomass measurements using airborne lidar, radar, and hyperspectral techniques should be evaluated further through field testing. Once a sampling strategy has been identified, these approaches can be used in conjunction with in situ measurements and modeling to develop continent-wide data on current carbon stocks, fluxes, and changes in stocks and fluxes.

Phase 2: Intensive Field Studies

Network Design Issues

Proposed designs from the preliminary phase will be rigorously tested and evaluated under field conditions.

Particular attention must be given to integrating the designs with atmospheric measurements.

Enhancements to Extensive Inventories

Compilation of historical data and support for intensive studies is required at this phase. It will be necessary to specifically test and evaluate field procedures to attain accurate and seamless extensive data collection. All relevant historical data should be compiled and available at the end of this phase. A major effort is required to address data gaps in extensive inventories by applying substitute methods based on remote sensing, alternative plot networks, and ecosystem models. This supplemental data should be fully compatible with existing inventory data except that the sources of information will be different.

Support for Initial Intensives

Support is needed for the initial intensives of the atmospheric measurements' "proof of concept" exercise (agricultural and urban test areas), and subsequent phasing of atmospheric measurements over a variety of cover classes. In addition, intensive field studies will be needed to develop and test the multi-tier sample design for land observations on models in representative cover classes. One or more intensive field studies will be needed in agricultural, urban/suburban, forest, wetland, and rangeland cover classes. If possible, such studies should be added to areas where significant intensive process monitoring is already underway, such as areas with AmeriFlux towers and/or LTER monitoring. This will make it possible to provide data on ecosystem response to climate change and to supply the required ground truth for a representative selection of sites.

During intensive field activities and in support of atmospheric sampling, in situ measurements of soil, leaf and canopy carbon and energy fluxes and carbon pools (including isotopic compositions) should be acquired. Additional activities should be conducted during intensive field campaigns:

- Monitoring disturbance (e.g., fire, forestry, agriculture) during a year of campaigns using satellite observations in combination with in situ measurements
- Monitoring phenology over the continent precisely (<= weekly, <= 1 km).
- Airborne remote sensing of state of vegetation—biomass, stress, and foliar chemistry—using lidar, radar, hyperspectral, multi-angle techniques.
- Developing a database of biophysical state (LAI/FPAR, soil moisture, meteorological conditions, inundation, disturbance such as fire, logging, other)
- Compiling appropriate descriptive historical data.

Phase 3: Long-Term Implementation

Based on preliminary studies and intensive campaigns, modifications to long-term networks will be proposed to broadly enhance the ability to monitor fluxes of major C species, and to control plant-soil characteristics and processes, for North America. Key limitations described earlier will be resolved: gaps in spatial coverage will be filled; complete ecosystem C stock changes will be estimated; and temporal resolution will be high (annual to monthly). Comprehensive data and analysis tools will facilitate development of predictive models to evaluate policy scenarios for managing greenhouse gases. Near-real-time, quality controlled data will be delivered to the sites for the data assimilation activities.

Appendix 3

Ocean Carbon Initiatives and Ocean Observations

Ocean Carbon Initiatives

Recent workshops sponsored by NSF, NOAA, and NASA identified research objectives to improve understanding of carbon dynamics in the ocean. Several themes were common among these federal agencies:

- What are the critical components of the ocean carbon cycle regulating the partitioning of CO_2 between the atmosphere and the ocean on seasonal to interannual time scales, and how can we improve prediction of the response of these processes to changes in environmental conditions (e.g., due to global warming)?
- How do we adequately characterize the non-steady-state behavior of oceanic systems?
- How do components of the ocean system—physical and ecological—move between semi-stable states?
- What are the stabilizing (negative) and destabilizing (positive) feedbacks inherent in the system?
- How can biological, physical, and chemical processes be more realistically represented in ocean carbon cycle models?
- What are the potential responses of marine ecosystems and ocean biogeochemical cycles to climate?

Implementation of any research effort that addresses ocean carbon cycling in a global context will require an integrated Earth systems approach that incorporates many disciplines and interagency partners. Below are brief descriptions of the interagency planning efforts for an ocean carbon program that directly address the scientific questions of the NACP.

NOAA GCC

The NOAA Global Carbon Cycle (GCC) Program currently focuses its efforts on the large-scale distributions and fluxes of CO_2 in the open ocean regions of the North Atlantic and North Pacific Oceans. Given adequate enhanced resources, the NOAA GCC program envisions a major expansion of sea surface CO_2 measurements and related properties in the North Atlantic and the North Pacific (including the equatorial Pacific), and potentially the coastal regions. The measurements will be made primarily using 8 to 12 volunteer observing ships (VOS), supplemented by time-series measurements. The North Atlantic and North Pacific studies will provide constraints for improved inverse model estimates of the North American carbon sink, yield robust values of air-sea CO_2 fluxes in the coastal and open ocean regions on both sides of North America, and give important and extensive new information about biogeochemical processes.

NSF CoOP

The NSF CoOP (Coastal Ocean Processes) Program is currently sponsoring research on the transport and controlling biogeochemical processes at a variety of U.S. margin environments. The CoOP research plan is to conduct process and modeling studies on shelves that differ in the dominant physical processes that influence cross-margin transport and control biogeochemical characteristics. CoOP studies thus attempt to isolate key processes that have some global generality and to study these in detail on margins where effects can be isolated with a maximum degree of confidence. Modeling studies are integrated with the process studies and used to synthesize and generalize study results. CoOP presently supports research programs along margins characterized by wind-induced transport on the coasts of California and Oregon.

NSF RiOMar

As a component of NSF's global carbon cycle research efforts, the RiOMar (River-dominated Ocean Margins) initiative focuses on process studies of carbon transformations and transport in continental margins impacted by major river inputs (such as the Mississippi River system in North America). The decadal-scale storage of terrestrial carbon within the terrestrial portions of some river systems may be much more important than previously recognized. Recent findings suggest that the age of DOC and POC being discharged from rivers is generally older and more variable (i.e., across different river systems) than previously believed. RiOMar systems are important global sites for burial of organic carbon and other biogeochemically important materials. Globally, about 90% of modern organic carbon burial occurs in RiOMar systems (deltas and associated shelf environments). Despite the prominence of sediment burial, large quantities of organic carbon are remineralized in RiOMar environments, as a result of diagenetic transformations and subsequent transport in dissolved or colloidal forms. Annually, the total organic carbon burial in marine sediments is equivalent to less than one-third of the riverine organic carbon discharge---indicating that riverine organic matter is rapidly mineralized or preferentially transported off the margin.

NASA Planning

NASA has conducted several workshops to plan an extensive program of observations of carbon cycling and air-sea fluxes in selected coastal and open ocean regions surrounding the continental United States and Alaska. The plans focus on quantification of air-sea CO_2 fluxes, carbon transport (including downward export out of the mixed layer), and biogeochemical transformations of carbon (e.g., photochemistry of DOC). The existing suite of satellite-observed ocean parameters includes surface winds (scatterometry and passive microwave radiometry), ocean circulation (altimetry), sea surface temperature (SST; infrared radiometry), and chlorophyll-*a* concentrations (ocean color) and primary production (ocean color with additional ancillary information on SST, mixed layer depth, surface irradiance, etc.). Future algorithm development efforts will focus on additional carbon products such as dissolved organic carbon, particulate organic carbon, new production, export production, phytoplankton functional groups (e.g., coccolithophores, trichodesium) and air-sea CO_2 fluxes using remote-sensing inputs. NASA currently has an airborne combination pulse-probe LIDAR/hyperspectral radiometer for phytoplankton and ocean carbon studies and an airborne microwave radiometer for ocean salinity measurements, both of which would be extremely useful for the coastal studies envisioned under the NACP. A satellite salinity mission has been proposed to the most recent Earth System Sciences Pathfinder program, but the evaluations have not been released as yet. NASA is also developing a lidar system for profiling particle concentrations from a ship or aircraft. Appendix 1 provides a summary of the relevant satellite and aircraft observations that are available, under development, approved, or under discussion for the next decade.

To better utilize remote-sensing data for understanding the underlying physical, biological, and chemical processes, investments have been discussed to develop refined ocean carbon cycle process and ecosystem models capable of integrating remote-sensing and in situ measurements. Related modeling activities are already underway as part of the NASA Seasonal-to-Inter-annual Prediction Program (NSIPP), which is developing methodologies for assimilating physical oceanographic data into global-scale coupled ocean-atmosphere numerical models. Development will integrate biological/chemical/physical modeling on several scales, including detailed process models, local and regional site-specific models, diagnostic, inverse and data assimilation models, and global ocean biogeochemical models.

Initial Concepts for Ocean Observations

The ocean observation component of the NACP is focused on addressing two basic issues: (1) How much carbon is sequestered by the oceans (coastal and open), in particular in the Northern Hemisphere? (2) How do energetic coastal processes influence atmospheric carbon dioxide in the marine boundary layer? The division between the open and coastal oceans is operationally defined as the boundary between the highly variable surface waters near the coast and the relatively stable offshore waters. The location of this boundary depends on the region and environmental conditions, generally from 50 to 500 km from shore (Figure A3.1). The open ocean and coastal observation networks outlined below are expected to develop in coordination with the ring of coastal atmospheric stations and will provide information for extended periods on interannual variability. The intensive work proposed in the Coastal Network section is planned for 2004–2006 to complement NASA and NSF field programs.

Open Ocean Network

The North Atlantic and North Pacific studies will provide information on the boundary conditions for the NACP and help place NACP data in a larger scale context, providing critical constraints for improved inverse model estimates of the North American carbon sink. The NACP will benefit greatly from implementation of existing and enhanced open ocean plans that focus on large-scale distributions and fluxes of CO_2 (see Bender et al., 2001). The primary component of these programs will be measurements of surface seawater and atmospheric CO_2 using automated shipboard instruments on 8 to 12 VOS that transit the North Pacific and North Atlantic. Ship tracks will repeat at monthly to seasonal intervals, with likely lines between Seattle and Tokyo, Los Angeles and Hong Kong, Southampton and Panama, and Lisbon and New York, designed to cover the range of oceanographic regions. Time-series stations located at key spots in the North Atlantic and North Pacific will provide data on higher frequency variability. Process studies in the

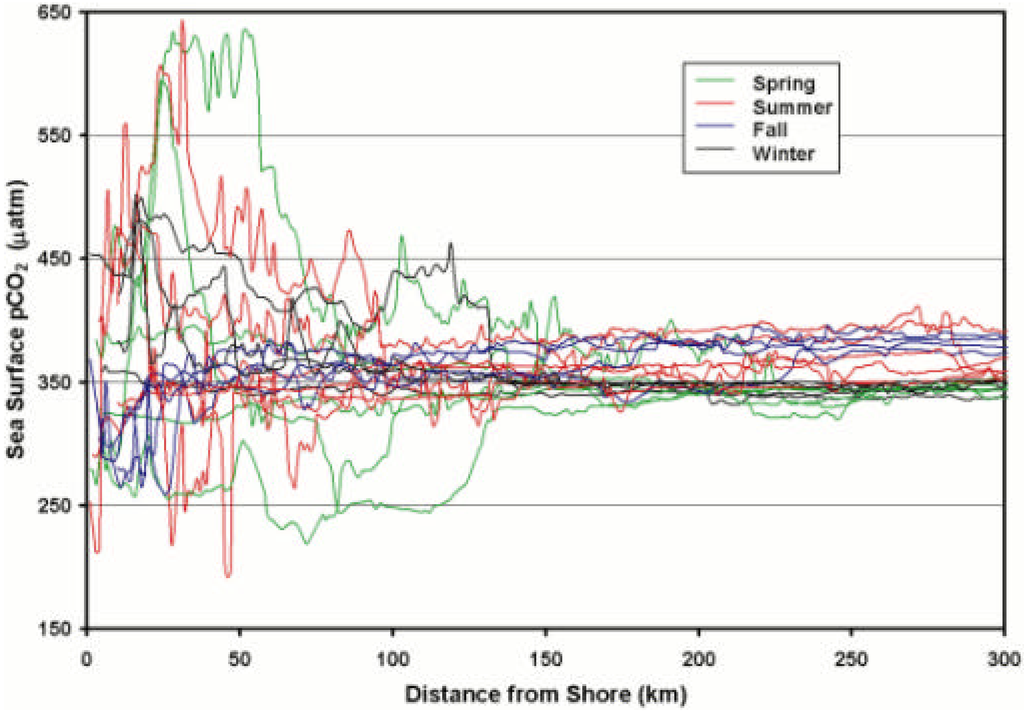

Figure A3.1. pCO_2 variability in surface waters across the continental margin of the west coast of the United States, showing the high degree of variability in coastal upwelling regions out to a distance of approximately 200 km from the coast (data provided by Francisco Chavez of MBARI).

North Atlantic and North Pacific will also contribute to the effort. These data will yield robust values of air-sea CO_2 fluxes in open ocean regions on both sides of North America, and will provide ocean-atmosphere fluxes to help constrain improved inverse model estimates of the North American carbon sink.

Long-term studies by programs like RiOMar will provide valuable information on land-ocean interactions and transformations. NACP will provide a forum for the coastal oceanography and terrestrial scientists to coordinate efforts and better ensure that no major source or sink regions in the wetland and coastal environments are missed. Both nearshore terrestrial and ocean scientists will work with atmospheric scientists to interpret signals observed in coastal towers and aircraft profiles.

NACP Coastal Ocean Network

The coastal ocean program for the NACP is envisioned as a set of meridional and zonal VOS ship transects and time-series stations, focusing on high-resolution observations of the air-sea fluxes of CO_2 in the continental margins of North America (Figure A3.2). The time-series moorings will make high-resolution measurements in the surface water and atmosphere, included calibrated data for atmospheric CO_2 comparable to CMDL island stations.

Monthly or seasonal transects perpendicular to the coast, intersecting the time-series moorings, will characterize the onshore-offshore gradients, placing the data from the moorings in a spatial context. Measurements will include basic meteorological and hydrographic data, atmospheric and oceanic pCO_2, organic carbon, nutrients, and primary production, allowing calculation of net oceanic CO_2 fluxes. The observations will be coordinated with aircraft surveys to obtain large-scale vertical and horizontal distributions of atmospheric CO_2. A limited number of sites in representative ecosystems will be intensively studied, including the Mid-Atlantic Bight, the South Atlantic Bight, the West Coast region, the Gulf of Maine, the Mississippi Delta region and the Bering Sea. These sites will be centered at the time-series moorings.

Coordination with Satellite Observations

Field observations required for algorithm development (bio-optical and atmospheric correction), satellite calibration and product validation, and model process parameterization and formulation to the greatest degree

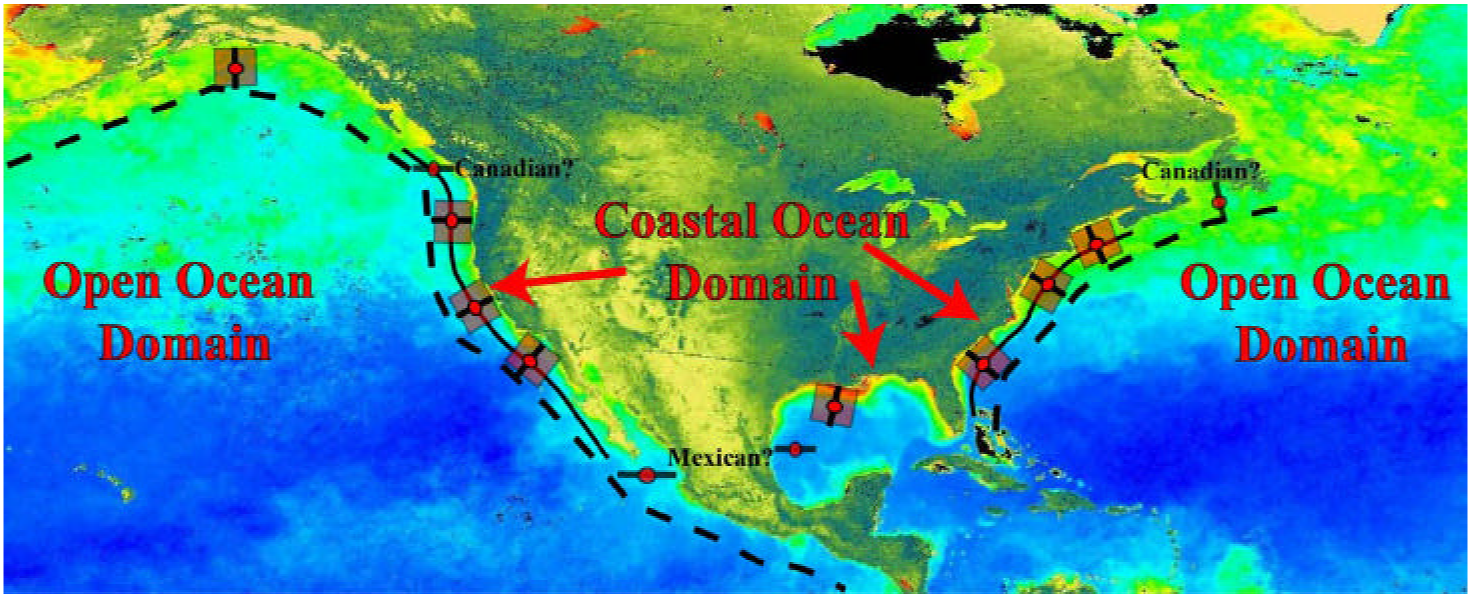

Figure A3.2. Proposed sampling domains for open-ocean and coastal regions within the scope of the NACP. Surface water pCO2 measurements and ancillary measurements will be made on VOS ships and moorings. The red dots show the locations of coastal time series and the black lines indicate time-series surveys.

possible will be acquired to ensure complete data sets. The field measurements will include inherent and apparent ocean optical properties, biological properties (species, pigments, photosynthetic rates, etc.), and chemical and hydrographic properties (salinity, nutrients, dissolved and particulate carbon concentrations, etc.). In most cases, these field experiments will be joint cruises with NOAA and NSF. The NASA strategy will be to augment open ocean sampling on NOAA and NSF cruises in the North Atlantic and North Pacific and at the Bermuda and Hawaii time-series sites. For the more complex coastal studies, a detailed interagency strategy will be developed to account for the use of smaller vessels (fewer investigators, hydrographic winches, wet lab space, etc.) and differing data collection strategies (time series, surveys, process studies, algorithm development, etc.). Algorithm development and process parameterization studies will require at least seasonal cruises in a variety of sites to capture the variability needed for these formulations. Suggested coastal sites for bio-optical algorithm development are the same regions suggested for the intensive studies.

The acquisition of observations will be coordinated for each cruise so to minimize redundancy, maintain data consistency and quality, and maximize data use. Finally, an interagency strategy for data submission, quality assurance, and management is being developed. One example of an existing data management arrangement is collaboration between the NASA Sensor Inter-comparison and Merger for Interdisciplinary Oceanic Studies (SIMBIOS) project and NOAA's National Oceanographic Data Center (NODC), where bio-optical data collected by NASA-supported investigators for ocean color algorithm development and product validation is provided to NODC for general distribution.

Appendix 4a

Satellite Remote Sensing and Data Assimilation Office (DAO) Contributions to NACP

There are a number of historical, on-orbit, approved, and proposed satellite missions that can contribute to the goals, both near term and long term, of the NACP. Table A4.1 provides a brief compilation of the instruments as they apply to the various processes associated with major land-ocean-atmosphere carbon flux categories, that is, air-sea CO_2 and carbon export (to the deep ocean), land-atmosphere CO_2, land-atmosphere CH_4, and land-sea carbon fluxes. In many cases, if not most, derivation of the specific carbon-related parameters sought from these data sets will need considerable investment in algorithm development and validation. The field experiments conducted under the NACP would offer opportunities for these purposes, but additional independent NASA-sponsored experiments will probably be required to obtain data sets of sufficient diversity and completeness. Note that Table A4.1 is not a comprehensive list of all land, ocean, and atmospheric Earth-observing missions and data sets that might be considered, but are those deemed most critical to the NACP. Also, missions in the time frame of the NACP that are important for aerosol radiation forcing evaluations are listed, because they may be of indirect use in some carbon budget analyses.

The NASA technology development program provides a progression of opportunities from the component level to demonstration missions. Table A4.1 entries include contributions from the Instrument Incubator Program (IIP), the New Millennium program, and the Earth System Sciences Pathfinder (ESSP). The IIP produces prototype instruments that may be deployed on aircraft. New Millennium missions such as EO-1 Hyperion (a passive hyperspectral imager) are satellite demonstrations with limited data acquisition and processing. The ESSP emphasizes a more comprehensive satellite observational and data-processing requirement, but with a limited duration (1 to 2 years); an example is the Vegetation Canopy Lidar (VCL). During the summer of 2001, the IIP and ESSP completed selections. IIP instruments that should be ready for the initial NACP field campaigns include passive and laser CO_2 airborne systems. The ESSP selections have not yet been announced. Existing/scheduled instruments in Table A4.1 might contribute to NACP measurement needs, but are far from optimal. The recent ESSP selection process offers the best chance for spaceborne observations to be applied to NACP goals.

Field data collection for process model development, remote-sensing algorithm development, and product validation should be integrated, in parallel with the NACP, and NASA should collaborate with other U.S. and international agencies.

Table A4.1

Remote-Sensing Contribution to Providing Ecosystem Variables Relevant to Carbon Cycle Studies

Component of Surface-Atmosphere Carbon Flux	Global Observation Required	Existing, Approved, or Proposed Instruments/Missions			Other Contributing Remote Sensors	Potential New Missions	Spatial Sampling Frequency	Temporal Sampling Frequency
		Historic	Current and Near-term	Through 2010				
Land-atmosphere CO_2 flux and terrestrial carbon storage	Atm. CO_2 variability		AIRS, TES, Envisat	TBD	IIP (FPI and LIDAR)	Active/Passive CO2 sensors	TBD	TBD
	Land cover type and change	AVHRR, Land Sat	AVHRR, LandSat 7, MODIS, ADEOSII, Envisat	LDCM, NPP	AVIRIS, AIRSAR	Synergistic multispectral optical + multifrequency polarimetric radar	30 m and 250-1,000 m	Seasonal
	LAI	AVHRR, Landsat	AVHRR, LandSat 7, MODIS, Envisat	MODIS,LDCM, ALOS, NPP	AIRSAR	Synergistic multispectral optical + radar missions	25-1000m	Monthly
	Biomass and regrowth			VCL , ALOS	AIRSAR, LVIS, SLICER	Wide-swath LIDAR + low-frequency polarimetric radar	50-100 m	Annually
	Wetland extent	AVHRR, Landsat, SIR-C, JERS-1	AVHRR, Landsat 7	ALOS, LDCM	AIRSAR	Low-frequency polarimetric radar	25 m or less, and ~1 km	Sub-weekly
	Soil moisture regime (surface and deep)	SSM/I	Envisat	TBD	AIRSAR, IIP (UHF/VHF radar)	Higher-resolution radiometers, lower-frequency radars	~5-50 km	3-day for surface, 10-day for depth
	Vegetation architecture or profile		MISR, ADEOSII	VCL	LVIS, SLICER, AIRSAR	Wide-swath LIDAR + interferometric radar	25-250 m	Annually
	Type/extent of disturbance	AVHRR, Landsat, ERS-1, JERS-1	AVHRR, Landsat 7, ADEOSII, Envisat	AVHRR, LDCM, ALOS,NPP	AVIRIS, AIRSAR	Follow-on missions	1-5 m, 30 m, and 250-1,000 m	Daily to seasonal
	Vegetation Productivity	AVHRR	MODIS, SeaWiFS, AVHRR, Envisat	NPP, ALOS		Follow-on missions	250-1,000 m	Daily to weekly
	Precipitation		TRMM	GPM	PR-2	Follow-on missions, geosynchronous	1 km	Daily
	Cloud cover	AVHRR	MODIS	CloudSat, NPP		Follow-on missions, geosynchronous	1 km	Daily
Land-atmosphere CH_4 flux	Atm. CH_4		MOPITT, AIRS,TES, Envisat				30-100 km	Daily

Component of Surface-Atmosphere Carbon Flux	Global Observation Required	Existing, Approved, or Proposed Instruments/Missions			Other Contributing Remote Sensors	Potential New Missions	Spatial Sampling Frequency	Temporal Sampling Frequency
		Historic	Present and Near-term	Through 2010				
Air-Sea CO flux and carbon export	Wind speed	ERS-1	Quickscat, ADEOSII	Seawinds follow-on		Follow-on missions	25 km	Daily
	Sea surface temperature	AVHRR	AVHRR, MODIS, Envisat	NPP			1 km	Daily
	Chlorophyll	CZCS SeaWiFS	SeaWiFS, MODIS, ADEOSII, Envisat	NPP		Ocean Carbon Mission	1 km	Daily
	Ocean productivity		MODIS, SeaWiFS, ADEOSII, Envisat	NPP		Ocean Carbon Mission	1 km	Daily
	Ocean organic carbon		ADEOSII		A/C particulate LIDAR	Ocean carbon mission	1 km	Daily
	Circulation & hydrography	TOPEX	JASON-1	JASON-2			300 km	10 day

The NASA Data Assimilation Office (DAO) has proposed the following work in support of the NACP.

A Tailored Meteorological Reanalysis

A 25-year reanalysis of the atmosphere and land surface is required in the plan. This product must be of high spatial resolution (either 50 km or 100 km), with a sufficient number of levels in the planetary boundary layer and troposphere to resolve transport processes of importance to carbon species, and with adequate temporal output of analyzed fields. Similar products are required by other communities (such as climate diagnostics and tropospheric and stratospheric chemists), but it is essential to maintain at least one output stream tailored to the needs of the NACP. Specific requirements of the NACP are (1) sufficient spatial and temporal resolution to resolve the transport of CO_2 and other gases, and (2) a suite of diagnostics that enable the effects of sub-grid-scale transport to be accounted for in calculations of the carbon budget. The product must be well validated, documented and quality-controlled; additionally, some measures of uncertainties are needed, particularly for the sub-grid-scale transport parameters.

The following will be specific uses of this reanalysis for the NACP:

1. Help spin-up of a comprehensive land model, including carbon species
2. Provide meteorological data to drive transport models used to calculate distributions of CO_2, CO, CH_4 and other gases, to determine interannual variability of transport and to guide development of the observing system
3. Provide boundary conditions for a nested, high-resolution regional assimilation system to produce detailed inventories of carbon species over the United States
4. Assist forecasting for and analysis of intensive field missions.

This reanalysis can only be produced by a center with operational capabilities. NASA's DAO, one such center, has indicated interest in working with the NACP science team toward providing this product. The reanalysis should be overseen by a steering committee including senior scientists, representatives from major data assimilation centers, and representatives of federal agencies. Maintaining quality and throughput will be a major effort.

The timeline for the project is as follows:

FY 2002

- Formation of the steering committee and the local (DAO) science team. Begin efforts to gather, format, and quality-control the input data. Incorporate the customized (high-frequency) output streams.
- Perform test analyses for target periods, provide these data to potential users, and complete comprehensive evaluations.
- Develop the monitoring system (modify from operational system).
- Prepare computing resources.

FY 2003

- Complete data gathering and preparation.
- Complete test analyses for target periods, provide these data to potential users, and complete comprehensive evaluations.
- Develop the monitoring system (modify from operational system).
- Prepare computing resources.

FY 2004

- Complete tests and development.
- Commence production and maintain throughput; monitor, validate and quality-control.
- Disseminate data to users.

FY 2005/2006–

- Complete to present, maintain production.

Development of a Carbon-Species Data Assimilation System (CSDAS)

Both off-line and on-line assimilation capabilities for CO_2 must be developed. One main objective is to develop an assimilation tool for global satellite observations. The DAO already assimilates trace gases (O_3, CO) and aerosols, and the assimilation effort for CH_4 and CO_2 will enhance this capability with multi-species assimilation, so that space-based observations of (say) CO can be used to help constrain CO_2 and CH_4. Target data sets in the near term will include AIRS and TES CO_2 and TES CH_4, along with MOPITT CO. The assimilation capability will initially be developed off-line (using meteorological data from the 25-year reanalysis) but will subsequently be applied to an on-line system, which will allow for more constraints (e.g., H_2O). This multi-species assimilation system would also form the basis of impact studies for future space-based missions.

Appendix 4b

Emissions Inventories in the NACP

A program to define the natural components of the cycle will require careful characterization of the human components. Doing so depends on (1) analysis of the spatial and temporal distributions of emissions and (2) understanding how efforts to control carbon flows in one area or for one set of processes will impact the full system. The detailed analyses in the NACP, both forward and inverse approaches, will require refined inventories of anthropogenic emissions of CO_2, CH_4, and CO, with detailed spatial and temporal distributions of emissions characterized by fuel in order to allow estimation of carbon isotope signatures. We also need a better description of the uncertainties in these values.

We envision that the requisite analyses of emissions would be carried out using a multi-phase strategy. The first phase would involve emissions inventories on the approximate scale of months and U.S. counties. The spatial and temporal distribution of sources is highly variable and later phases will better describe the variability with time of day, day of the week, and weather, for example. We would be interested to know the extent to which these variations can be described with simple algorithms. What are the linkages between human emissions and the climate system?

Validation of emissions estimates will be part of the intensive measurement phase, using the comprehensive suite of gaseous and particulate tracer species available for INTEX and other atmospheric chemistry missions. Emissions from large point sources can be highly variable on small temporal and spatial scales as power plants are taken down for maintenance and adjusted to meet load demand. In the context of specific focused campaigns to understand the functioning of the North American carbon cycle, it is possible to think in terms of human emissions, especially those from large point sources, as a variable that might be manipulated.

ACRONYMS

ADEOSII – Advanced Earth Observing Satellite, Japan
AES - Atmospheric Environment Service
AIRS – Atmospheric Infrared Sounder
AIRSAR – Airborne Synthetic Aperture Radar
ALOS – Advanced Land Observing Satellite, Japan
AVHRR – Advanced Very High Resolution Radiometer
AVIRIS – Airborne Visible/Infrared Imaging Spectrometer
BOREAS – Boreal Ecosystem Study
CASMGS – Consortium for Agricultural Soils Mitigation of Greenhouse Gases
CBL – Continental Boundary Layer
CCI – Carbon Cycle Initiative
CCIWG – Carbon Cycle Interagency Working Group
CCSP – Carbon Cycle Science Plan
CDIAC – Carbon Dioxide Information Analysis Center
CMDL – Climate Modeling and Diagnostics Laboratory
COBRA 2000 – CO_2 Boundary-layer Regional Airborne experiment 2000
CoOP – Coastal Ocean Processes
CSDAS – Carbon-Species Data Assimilation System
CZCS – Coastal Zone Color Scanner
DAO – Data Assimilation Office
DGVMS – Dynamic Global Vegetation Models
DIAL – Differential Absorption Lidar
DIC – Dissolved Inorganic Carbon
DOE – Department of Energy
DOC – Dissolved Organic Carbon
ECMWF – European Centre for Medium-Range Weather Forecasts
EEC – Engineering Education and Centers
ENSO – El Niño-Southern Oscillation
Envisat – Environmental Satellite
EOS – Earth Observing System
ERS – European Remote Sensing Satellite
ERS-1 – Japan Earth Resources Satellite
ESSP – Earth System Sciences Pathfinder
FACE – Free Air Carbon Exchange
FIA – Forest Inventory Analysis
FPAR – Fraction of Photosynthetically Active Radiation
FPI – Fabry-Perot Interferometer
FT – Free Troposphere
GCC – Global Carbon Cycle
GFDL – Geophysical Fluid Dynamics Laboratory
GPM – Global Precipitation Mission
GPP – Gross Primary Productivity
GTE – Global Tropospheric Experiment
IIP – Instrument Incubator Program;
INTEX-NA – Intercontinental Transport Experiment-North America
IOP – Intensive Operation Periods
LAI – Leaf Index Area
LandSat – Land Remote-Sensing Satellite
LDCM – LandSat Data Continuity Mission
LSCOP – Large Scale CO_2 Observation Plan
LTER – Long-Term Ecological Research
LVIS – Laser Vegetation Imaging Sensor
MISR – Multi-angle Imaging Spectroradiometer
MODIS – Moderate-Resolution Imaging Spectroradiometer
MOPITT – Measurements of Pollution in the Troposphere
NACP – North American Carbon Program
NAS – National Academy of Sciences
NCAR – National Center for Atmospheric Research
NCEP – National Centers for Environmental Prediction
NDIR – Non-Dispersive Infrared
NDVI – Normalized difference vegetation index
NEE – Net Ecosystem Exchange of Carbon
NODC – National Oceanographic Data Center
NPOESS – National Polar-orbiting Operational Environmental Satellite System
NPP – Net Primary Productivity
NRI – National Resources Inventory
NSF – National Science Foundation
NSIPP – NASA Seasonal-to-Inter-annual Prediction Program
NWP – Numerical Weather Prediction
NWS – National Weather Service
OMB – Ocean Modeling Branch
OMI – Ozone Monitoring Instrument
PBL – Planetary Boundary Layer
pCO2 – Partial Pressure of Dissolved CO_2
PgC – Picograms of Carbon (10^{15} g)
PR-2 – Second Generation Precipitation Radar
QA/QC – Quality Assurance/Quality Control
RAMS – Real-time Analysis of Multi-channel Signals
RioMar – River-dominated Ocean Margins
SAGE – Stratospheric Aerosol and Gas Experiment
SeaWiFS – Sea-viewing Wide Field-of-view Sensor
SIMBIOS – Sensor Inter-comparison and Merger for Interdisciplinary Oceanic Studies
SIR-C – Shuttle Imaging Radar
SLICER – Scanning Lidar Imager of Canopies by Echo Recovery
SSM/I – Special Sensor Microwave/Imager
SST – Sea Surface Temperature
TES – Tropospheric Emission Spectrometer
Tg – Teragrams (10^{12}g)
TM – Thematic Mapper
TOMS – Total Ozone Mapping Spectrometer
TOPEX – Ocean Topography Experiment
TRMM – Tropical Rainfall Measuring Mission
USDA – U.S. Department of Agriculture
VCL – Vegetation Canopy Lidar
VOS – Volunteer Observing Ships
WMO – World Meteorological Organization

References

Battle, M., M.L. Bender, P.P. Tans, J.W.C. White, J.T. Ellis, T. Conway, R.J. Francey, 2000: Global carbon sinks and their variability inferred from atmospheric O2 and 13C. *Science*, **287**, 2467–2470.

Barford, Carol C., S.C. Wofsy, M.L. Goulden, J.W. Munger, E.H. Pyle, S P. Urbanski, L. Hutyra, S.R. Saleska, D.R. Fitzjarrald, and K. Moore, 2001: Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest, *Science*, 1688–1691.

Bakwin, P.S, P.P. Tans, D.F. Hurst, and C.L. Zhao, 1998: Measurements of carbon dioxide on very tall towers: Results of the NOAA/CMDL program. *Tellus* B, **50**(5): 401–415.

Baldocchi D, E. Falge, L.H. Gu, R. Olson, D. Hollinger, S. Running, P. Anthoni, C. Bernhofer, K. Davis, R. Evans, J. Fuentes, A. Goldstein, G. Katul, B. Law, X.H. Lee, Y. Malhi, T. Meyers, W. Munger, W. Oechel, K.T. Paw,, K. Pilegaard, H. P. Schmid, R. Valentini, S. Verma, T. Vesala, K. Wilson, and S. Wofsy, 2001: FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities.. *Bulletin of the American Meteorological Society*, **82**(11), 2415–2434.

Behrenfeld, M. J., J. T. Randerson, C. R. McClain, G. C. Feldman, S. Q. Los, C. J. Tucker, P. G. Falkowski, C. B. Field, R. Frouin, W. E. Esaias, D. D. Kolber, and N. H. Pollack. 2001. Biospheric primary production during an ENSO transition, *Science*, 291: 2594-2597.

Bender, M. et al., 2001: *A U.S. Large-Scale CO_2 Observing Plan: Oceans and Atmosphere*. Report for the Carbon Cycle Interagency Working Group. Washington, DC: US Global Change Research Program. (Available on line at ww.ogp.noaa.gov/mpe/gcc/co2/observingplan/toc.htm)

Caspersen, J. P., S. W. Pacala, J. C. Jenkins, G. C. Hurtt, P. R. Moorcroft, and R. A. Birdsey. 2000. Contributions of land-use history to carbon accumulation in U.S. forests, *Science*, 290: 1148-1151.

Crill, P., K. Hargreaves, and A. Korhola, 2000: The role of peat in Finnish greenhouse gas balances. *Studies and Reports 10/2000*. Helsinki, Finland: Ministry of Trade and Industry.

Curtis, P.S., P.J. Hanson, P. Bolstgad, C. Barford, J.C. Randolph, H.P. Schmid, and K.B. Wilson, 2002: Biometric and eddy-covariance based estimates of annual carbon storage in five eastern North American deciduous forests. *Global Biogeochemical Cycles* (in press).

Engelen, R.J., G.L. Stephens, and A.S. Denning, 2001: The effect of CO_2 variability on the retrieval of atmospheric temperatures. *Geophysical Research Letters*, **28**, 3259–3262.

Engelen, R.J., A.S. Denning, K.R. Gurney, and G.L. Stephens. (in press): Global observations of the carbon budget: I, Expected satellite capabilities in the EOS and NPOESS eras. *Journal of Geophysical Research*.

Gerbig, C., J. Lin, and S.C. Wofsy, 2001: Quantification of regional and continental-scale surface fluxes of carbon using airborne measures in a Lagrangian framework. Paper B41A-04, American Geophysical Union Spring Meeting held in Boston, MA, May.

Kurz, W.A., and M.J. Apps, 1999: A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecological Applications*, **9**, 526–547.

Harden, J.W., E.T. Sundquist, R.F. Stallard, and R.K. Mark, 1992: Dynamics of soil carbon during deglaciation of the Laurentide ice-sheet. *Science*. **258**(5090), 1921–1924.

Lin, J.C., C. Gerbig, and S.C. Wofsy, 2001: Atmospheric constraints on terrestrial exchanges at the regional to continental scales. Paper B51C-07 presented at the American Geophysical Union Fall Meeting held in Boston, MA.

NAS (National Academy of Sciences), 2001: *Climate Change Science: An Analysis of Some Key Questions*. Washington, DC, National Academy Press.

Pacala, S.W., G.C. Hurtt, R.A. Houghton, R.A. Birdsey, L. Heath, E.T. Sundquist, R.F. Stallard, D. Baker, P. Peylin, P. Ciais, P. Moorcroft, J. Caspersen, E. Shevliakova, B. Moore, G. Kohlmaier, E. Holland, M. Gloor, M.E. Harmon, S.-M. Fan, J.L. Sarmiento, C. Goodale, D. Schimel, and C.B. Field, 2001: Convergence of land- and atmosphere-based U.S. carbon sink estimates. *Science*, **292**, 2316–2320.

Potosnak, M.J., S.C. Wofsy, A.S. Denning, T.J. Conway, J.W. Munger, and D.H. Barnes, 1999: Influence of biotic exchange and combustion sources on atmospheric CO_2 concentrations in New England from observations at a forest flux tower. *Journal of. Geophysical. Research*, **104**, 9561–9569.

Rayner, P.J., W. Knorr, M. Scholze, R. Giering, T. Kaminski, M. Heimann, and C. LeQuere, 2001: Inferring terrestrial biosphere carbon fluxes from combined inversions of atmospheric transport and process-based terrestrial ecosystem models. *Extended Abstracts*, Sixth International CO_2 Conference, Sendai Japan, MB17.

Running, S.W., C.O. Justice, V. Salomonson, D. Hall, J. Barker, Y.J. Kaufmann, A.H. Strahler, A.R. Huete, J.-P. Muller, V. Vanderbilt, Z.M. Wan, P. Teillet, and D. Carneggie, 1995: Terrestrial remote sensing science and algorithms planned for EOS/MODIS, *International Journal of Remote Sensing*, **15**(17): 3587–3620.

Sarmiento, J.L., and S.C. Wofsy, 1999: *A U.S. Carbon Cycle Science Plan*. Report of the Carbon and Climate Working Group. Washington, DC: U.S. Global Change Research Program.

Takahashi, T., S.C. Sutherland, C. Sweeney, A. Poisson, N. Metzl, B. Tilbrook, N. Bates, R. Wanninkhof, R.A. Feely, C. Sabine, and J. Olafsson, 2001: Biological and temperature effects on seasonal changes of pCO_2 in global ocean surface waters. *Deep-Sea Research* (in press).

Tans, P.P., P.S. Bakwin, and D.W. Guenther, 1996: A feasible global carbon cycle observing system: A plan to decipher today's carbon cycle based on observations. *Global Change Biology*, **2**, 309–318.

Wang, Y.P., and D.J. Barrett, 2001: Estimation of carbon exchange fluxes in Southern Australia using multiple constraints. *Extended Abstracts*, Sixth International CO_2 Conference, Sendai Japan, TE51.