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Science and Observation Recommendations for Future NASA Carbon Cycle Research

C.R. McClain, F.G. Hall, G.J. Collatz, S.R. Kawa, W.W. Gregg, J.C. Gervin, J.B. Abshire, A.E. Andrews, C.D. Barnet, M.J. Behrenfeld, P.S. Caruso, A.M. Chekalyuk, L.D. Demaio, A.S. Denning, J.E. Hansen, F.E. Hoge, R.G. Knox, J.G. Masek, K.D. Mitchell, J.R. Moisan, T.A. Moisan, S. Pawson, M.M. Rienecker, S.R. Signorini, and C.J. Tucker

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Goddard Space Flight Center
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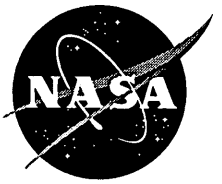

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NASA Goddard Space Flight Center, Greenbelt, Maryland

F.G. Hall, C.D. Barnet, and S. Pawson, University of Maryland, Baltimore, Maryland

P.S. Caruso, Swales Aerospace

A.M. Chekalyuk, Hampton University

A.S. Denning, Colorado State University

J.E. Hansen, NASA Goddard Institute of Space Science

F.E. Hoge, J.R. Moisan, and T.A. Moisan, NASA Wallops Flight Facility

K.D. Mitchell, Science Systems and Applications, Inc.

S.R. Signorini, Science Applications International Corporation

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Abstract

Between October 2000 and June 2001, an agency-wide planning effort was organized by elements of NASA Goddard Space Flight Center (GSFC) to define future research and technology development activities . This planning effort was conducted at the request of the Associate Administrator of the Office of Earth Science (Code Y), Dr. Ghassem Asrar, at NASA Headquarters (HQ). The primary points of contact were Dr. Mary Cleave, Deputy Associate Administrator for Advanced Planning at NASA HQ and Dr. Charles McClain of the Office of Global Carbon Studies (Code 970.2) at GSFC.

During this period, GSFC hosted three workshops to define the science requirements and objectives, the observational and modeling requirements to meet the science objectives, the technology development requirements, and a cost plan for both the science program and new flight projects that will be needed for new observations beyond the present or currently planned. The workshops were attended by Code Y program managers from HQ, the National Oceanic and Atmospheric Administration (NOAA), the Department of Energy (DOE), the Department of Agriculture (USDA), the U. S. Forestry Service (USFS), and the Office of Management and Budget (OMB). Also, representatives from the academic science community were invited to participate. The three workshops were designed to provide a stepwise progression from the definition of the science goals and objectives through the formulation of the science and technology roadmaps and budget projections. Each workshop consisted of plenary and discipline break-out sessions with members of the GSFC staff leading the discussions. After each workshop, the break-out session leaders provided summaries of their sessions which were used to formulate the agenda of the next workshop and finally presentation packages for GSFC and HQ management.

The plan definition process was very intensive as HQ required the final presentation package by mid-June 2001. This deadline was met and the recommendations were ultimately refined and folded into a broader program plan, which also included climate modeling, aerosol observations, and science computing technology development, for contributing to the President's Climate Change Research Initiative. This technical memorandum outlines the process and recommendations made for cross-cutting carbon cycle research as presented in June. A separate NASA document outlines the budget profiles or cost analyses conducted as part of the planning effort.

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1.0 INTRODUCTION AND BACKGROUND

Over the past 420,000 years, paleo-climate studies show the Earth's average surface temperature to have remained relatively stable, at least within the narrow range suitable for life (Figure 1), while the climates of other planets, e.g., Venus and Mars, are well outside this range. What are the causes of this co-variation? For one, the ocean "biological pump", the photosynthetic up take of atmospheric CO_2 by ocean microorganisms, results in long-term sequestration of carbon in the deep ocean via sedimentation, where it is slowly buried in sedimentary carbonates. The ocean "solubility pump" also removes atmospheric CO_2 as air mixes with and dissolves into the upper ocean. Vegetation on land sequesters carbon (about half the global photosynthetic uptake), until it is released back into the atmosphere by fire, logging, disease or mortality. Plant roots, litter and soil microorganisms inject carbon to the soil and are stored until they decompose. Prior to the Industrial Revolution, the annual uptake and release of CO_2 by the land and ocean had been on average just about balanced (Figure 2). However, looking at more recent history, concentrations have risen very rapidly over the past 150 years by over 80 ppm to current levels of about 360 ppm. This increase has motivated much attention recently, including the collection of temperature and greenhouse gas data sets such as the Vostok ice cores. Much of this data archived by the Department of Energy Carbon Dioxide Information Analysis Center (DOE/CDIAC) and is discussed in the lastest report from the Intergovernmental Panel on Climate Change (IPCC, 2001).

How has this regulation over such a narrow range been maintained over such a long period in the Earth's history? While variations in the Earth's climate are caused by a number of factors external to the climate system (land-ocean-atmosphere), including variations in the Earth's orbit about the sun, the orientation of its rotational axis with respect to the Earth-Sun plane, and even variations in the intensity of the sun's radiant output, major regulators of climate change are "internal", including processes associated with the carbon cycle and photosynthesis (Figure 3). Warming of the Earth's climate is driven primarily by the absorption of solar energy by heat-absorbing biologically generated "greenhouse" gases such as carbon dioxide and methane, and light-absorbing aerosols such as smoke and soot. Cooling results from reflective clouds and other aerosols such as dust. Removal of greenhouse gases by the Earth's terrestrial vegetation and its oceans by photosynthesis also acts to cool the Earth.

A comparison of Figure 1 with Figure 4, the Vostok ice core record of carbon dioxide concentrations in the Earth's atmosphere, displays a strong carbon-climate connection through co-variations over the past 420,000 years in the Earth's climate and its greenhouse gas concentrations. Similarly, as atmospheric CO_2 concentration has increased over the last century, a concomitant increase in average global temperatures of about 1°C have also been observed (Figure 5) with more rapid warming at high latitudes within continental interiors.

The contribution to the observed temperature change comes from several quarters. Figure 6 (see Hansen et al., 1998) separates changes in both climate warming (red) and cooling (blue) from 1850 to the present into its various causes (expressed as a "Forcing" or change in the amount of solar energy absorbed by the Earth (watts m^{-2}). The error bars are the estimated uncertainties in the magnitudes of the various contributions, reflecting primarily uncertainty in the rates of change of the various sources, or in some instances their precise climate impacts. Clearly, carbon dioxide and methane, hence the carbon cycle, have played an important role in climate change, and involve the atmospheric increases due to increased human activity and the mitigating effects of terrestrial and oceanic uptake of CO_2.

Examining the Earth's carbon budget in Figure 7, the climate-carbon connection can be clearly seen. The annual increase in atmospheric CO_2 of about 3 petagrams/year results from the emission of nearly 7 petagrams/year of carbon from the combustion of fossil fuels. However, roughly half is absorbed each by the land (2 petagrams/year) and oceans (2 petagrams/year), resulting in a much slower increase in atmospheric carbon dioxide. Thus, these natural ecosystems provide a service to the global economy worth billions of dollars through natural mitigation of climate change. The reasons for this capacity of the Earth's land and oceans to absorb carbon dioxide are not adequately understood, and future uptake by the land and ocean cannot be estimated. Given the importance of forecasting climate change to the nation, it is of utmost urgency to find out.

In the remainder of this proposal, we will define a number of strategic new investments within NASA Earth Science Enterprise (ESE) that, when coordinated with the efforts of other agencies, will greatly accelerate our understanding of the global carbon cycle and its relationship to future climate change. We will first discuss the current state of knowledge about the carbon cycle. Then we will describe NASA's ongoing efforts to study it, as well as what carbon cycle research activities are currently supported by the various agencies and organizations involved in carbon cycle science. We will outline how NASA can cooperate with them, and why we think an additional strategic investment is needed to fill critical gaps in our observational and modeling capabilities. Finally, we will propose a prioritized slate of new studies and new technologies, schedules for each with optional satellite observation scenarios, and the associated timeline for program deliverables, products, and results.

1.1 Current state of carbon cycle science and uncertainties

In the late 1950's, Charles Keeling, a graduate student at the time, began a series of measurements on a mountain peak in Mauna Loa Hawaii, to examine the hypothesis that the burning of fossil fuels might be causing atmospheric CO_2 concentrations to increase. His data were soon to confirm this hypothesis. Since his initial experiment, there have been a continuous and increasing number of atmospheric CO_2 measurements worldwide. Currently, measurements at nearly 70 sites, mostly over the ocean, are made on a regular basis and have shown that the atmospheric carbon content increases on average by about 3 petagrams annually with an uncertainty of less than 10% (Figure 8).

Analyses of economic data pertaining to the sale and use of fossil fuels show that at the end of the 20^{th} century, more than 7 petagrams of carbon are released annually, again with a reasonably small uncertainty of less than 10%. Thus, on average, 4 petagrams or more than half the annual increase in atmospheric carbon is removed from the atmospheric by natural processes occurring in the ocean and on the land, sometimes referred to as the "missing sink". Where has this carbon gone? Ship-borne measurements of the ocean surface CO_2 concentration show a differential concentration with the atmosphere that suggests that the ocean may be absorbing about 2 of the 4 petagrams. The remaining 2 petagrams by inference must be taken up by an "unidentified sink" somewhere on land. Where is this sink?

The mean concentration gradient of CO_2 from the southern to the northern hemisphere is only 3 to 4 ppmv and exists because most of the fossil fuel CO_2 is emitted in the north. "Inverse" methods to trace these atmospheric gradients back to their surface sources are uncertain given only 70 regular global measurements of CO_2. Nonetheless, the inverse analyses indicate there is a land sink in the northern mid-latitudes, which in recent decades has amounted to 1.5 Pg C/year, agreeing reasonably well with the budget calculations of Figure 8. Unless and until we can locate

the sinks more accurately, and determine the cause of the carbon sequestration and how it might depend on future climate, our capability to predict the impact of the carbon cycle on future climate will be seriously limited.

Our present understanding of the Earth's ocean, land and atmosphere carbon exchange is captured in global, long-term climate and other observations and in simulation models which attempt to describe biological (e.g., photosynthesis and respiration) and physical (e.g., ocean and atmospheric circulation) processes and the interactions between them. Models are particularly useful for inferring cause and effect and for quantifying the magnitudes of processes and feedback interactions. But these processes are complex and are incompletely captured by current model formulations.

As an example, Figure 9 displays state of the art model-based projections (red and blue lines) of future global average atmospheric temperatures. Both models have an interactive biosphere that responds to climate and affects the greenhouse gas content of the atmosphere and thus climate. However, future atmospheric greenhouse gas and climate projections from these two models vary widely, primarily because of different assumptions in these two models about how the Earth's biosphere will respond to climate warming. The Hadley Center model (Cox et al., 2000) has projected an atmospheric CO_2 level of nearly 1000 ppm in 2100, more than 200 ppm greater than the Institut Pierre Simon Laplace (IPSL) model (Friedlingstein et al., 2001). The primary differences in the two models are assumptions regarding the response of forests in the Amazon basin to future climate change. The Hadley Center model projects a replacement of the Amazonian rain forest by grasslands as the tropical climate warms and dries, with a subsequent loss of carbon to the atmosphere. The IPSL model does not. How can we know which projection is correct?

In order to characterize current carbon cycling and to predict future atmospheric carbon content and climate, coupled ocean-atmosphere-land surface system models are needed. Components of this system are being developed, but a number of processes are not accurately parameterized and full coupling of the model components along with sensitivity testing and evaluation with data is a long-term development effort. These models will need additional development, testing and validation to render reliable and practical global and regional projections of climate change. These efforts will require detailed laboratory and field observations and long-term global measurements of key parameters and forcing fields, including land and ocean vegetation distribution and abundance. Measurements of the rates of photosynthesis and respiration (plants and soil), atmosphere-surface exchanges of CO_2 and CH_4, as well as more standard meteorological variables such as radiation, rainfall, air temperature, and humidity will be needed. Although there are global networks of ground and ocean surface stations to measure some of these, most can only be acquired over vast and inaccessible areas of the globe using satellites.

While the previous discussion has focused on the effect of the carbon cycle on climate through its regulation of atmospheric CO_2, other carbon compounds are also important greenhouse gases (Figure 3). This CO_2-centric focus is justified to some extent because in comparison to other greenhouse gases such as CH_4, nitrous oxide and O_3, CO_2 is relatively stable chemically, with a long lifetime (~ 100-200 years) in comparison to transport times between the ocean and land surface. In addition, while CH_4 is radiatively important, the current concentration of CH_4 is a factor of 200 less than CO_2 and CH_4 is oxidized to CO_2 on relatively short time scales. Similarly, CO concentration is less than 1/1000 of CO_2. CO emissions from fossil fuel and biomass burning are generally included as CO_2 emissions since CO is oxidized to CO_2 within

days to weeks. However, recent atmospheric chemistry and transport modeling shows that CO may act as a temporary atmospheric reservoir of anthropogenic carbon leading to a carbon redistribution from regions where OH is small (winter high latitudes) to those where OH is greater (low latitudes). This process is not included in most transport model comparisons with data (e.g., inverse calculations).

1.2 Reducing Uncertainty and Understanding the Carbon Cycle

Two main and complementary approaches to quantifying and understanding carbon fluxes between the land, the ocean, and atmosphere are "bottom-up" and "top-down" approaches. The bottom-up method quantitatively characterizes the various carbon exchange processes between the earth's surface and the atmosphere and then "scales-up" the resultant understanding (captured in simulation models) from local to regional and global scales. Ocean and land bottom-up models can be coupled with each other and atmospheric models to compute instantaneous, seasonal and interannual variations in carbon flux as a function of surface "state" and climate forcing data for regional and global studies. Comparisons of predictions among the various bottom-up approaches show some convergence between spatial patterns of flux and their variation with climate, but there is also considerable disagreement that currently cannot be resolved in favor of one model or the other. Regional measurements of CO_2 flux (beyond a few kilometers using aircraft) do not yet exist. This problem is partially addressed with the complementary top-down approach, which uses observed temporal and spatial changes in global atmospheric gas concentrations (currently, there are only 70 CO_2 flask sampling sites around the world) to estimate global and regional CO_2 flux patterns on a regular basis. With the top down approach, one uses an atmospheric transport scenario (global wind fields for example) to solve for the most likely spatial and temporal pattern of surface-to-atmosphere carbon fluxes that could produce a particular set of observed global or regional atmospheric CO_2 concentrations. This approach is the primary line of evidence for a northern hemisphere carbon sink. Geographic patterns of atmospheric CO_2 concentrations vary from season to season and from year to year, thus the top down approach reveals dramatic interannual variations in ocean and land flux patterns that seem to be driven by seasonal and interannual climate variations. Top-down estimates when compared with bottom-up estimates of carbon flux provide validation of the bottom-up predictions, while the bottom-up approach improves our understanding of the underlying causes for the spatial and temporal variations. A number of top-down analyses have been conducted. They disagree to some extent as to the spatial structure of the sources and sinks. Error analyses show, however, that a major source of the disagreement lies with the sparsity of atmospheric concentration measurements rather than the top-down approach itself.

1.3 U.S. and International Carbon Cycle Science Programs

Over the past decade science and policy communities have come to recognize that in order to predict the consequences of global change and human activities, new concerted research and development efforts must focus on carbon cycle science at multiple temporal and spatial scales. Many international and U.S. programs are currently focusing on the important science and policy issues tied to the global carbon cycle (Figure 10).

The IPCC was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) to assess the available scientific, technical, and socioeconomic information in the field of climate change. The U.S. scientific

community participates extensively in IPCC assessments, and the U.S. hosts the Technical Support Unit for IPCC Working Group II on Impacts, Adaptation, and Vulnerability.

The International Human Dimensions Program (IHDP) on Global Environmental Change is concerned with how humans interact with the environment, how individuals and societies can mitigate or adapt to environmental change, and how policy responses to such changes influence economic and social conditions. Key IHDP programs underway address land use and land cover change and "institutional dimensions" of global environmental change.

The International Geosphere-Biosphere Program (IGBP) has as a goal to describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system, the unique environment that this system provides for life, the changes that are occurring in this system, and the manner in which these changes are influenced by human actions. U.S. programs coordinated through IGBP include the Joint Global Ocean Flux Study (JGOFS), the Global Ocean Ecosystem Dynamics project, and the Past Global Changes project. The IGBP has the lead role in work on the global carbon cycle. The Global Analysis, Interpretation, and Modeling (GAIM) program is IGBP's task force on carbon. The carbon cycle initiative of the IGBP will become part of a larger consortium based on interaction with the World Climate Research Program (WCRP) and the IHDP, and will become an inter-program crosscutting activity.

The purpose of the WCRP is to develop the fundamental scientific understanding of the climate system and climate processes that is needed in order to determine the extent to which climate can be predicted, and the extent of human influence on climate. The Climate Variability and Predictability Program (CLIVAR) and Global Energy and Water Cycle Experiment (GEWEX) are coordinated through the WCRP.

The Integrated Global Observing Strategy Partnership (IGOS-P) brings together a wide range of international, intergovernmental, and non-governmental organizations to develop a global observing strategy to meet the needs of global change research and of operational science programs. Key partners include the WCRP, IGBP, IHDP, WMO, UNEP, Intergovernmental Oceanographic Commission (IOC), the Food and Agriculture Organization (FAO), the International Group of Funding Agencies for Global Change Research (IGFA), the Committee on Earth Observation Satellites (CEOS), and the International Council of Scientific Unions (ICSU). The Global Terrestrial Observing System (GTOS)-Global Climate Observing System (GCOS)-IGBP partnership is designed to build the scientific research-observation community linkages in the most effective and efficient way possible. The work plan outlined for 2000 aims to make use of planned GTOS, GCOS and IGBP meetings in a collaborative way to achieve both observation design (GTOS-GCOS) as well as contributing to an internationally coherent carbon framework focused on research planning and synthesis (IGBP) objectives.

In 1989, Congress authorized the Global Change Research Act of 1990, a statute that directed the implementation of a US Global Change Research Program (USGCRP) aimed at "understanding and responding to global change, including the cumulative effects of human activities and natural processes on the environment." The USGCRP works with individual international partners to develop integrated modeling, observational, and process research programs and activities to: (1) identify and quantify regional- to global-scale sources and sinks for carbon dioxide and other greenhouse gases and understand how these sources and sinks will function in the future; and (2) identify and quantify regional- to global-scale atmospheric transport and precipitation of water (which control the principal input of hydrological process and water-resource models) and study the global water cycle as a unifying theme that can bridge

the gap in the spatial-scale spectrum between atmospheric and hydrological sciences. The latter effort will be coordinated nationally through planning underway to develop joint interagency programs and internationally through international programs that address water cycle research, e.g., CLIVAR, the GEWEX, and the Biospheric Aspects of the Hydrological Cycle program). Both of the above-cited new international efforts are critical to development of climate databases and the prediction systems that utilize them.

More recently the National Research Council (NRC) produced a report, "Global Environmental Change: Research Pathways for the Next Decade," that specifically emphasized the need for a comprehensive carbon cycle research strategy for the nation. In response, the USGCRP established the Carbon Cycle Science Program as a specific fundamental interdisciplinary research element. The purpose of the new program is to coordinate and integrate carbon cycle research across relevant US agencies in order to provide critical unbiased scientific information on the fate of carbon dioxide in the environment.

A carbon cycle interagency working group (IWG), composed of representatives from NASA, NOAA, USDA, DOE, National Science Foundation (NSF), USGS and USFS and guided by a science working group, is developing an implementation plan and a long term (10 year) strategy for an integrated research program. Implementation of the new program will require a significant investment of resources and a high level of interagency coordination and integration.

The general carbon cycle science goals that have been identified or adopted by the IWG are outlined in detail in Appendix 1 and are:

- 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: Evaluate the impact of land use change and terrestrial and marine resource management practices on carbon sources and sinks.
- Goal 5: Provide greatly improved projections of future atmospheric concentrations of CO_2.
- Goal 6: Develop the scientific basis for societal decisions about management of CO_2 and the carbon cycle.

In order to address these goals, the IWG has defined a set of research objectives and activities for the next decade. U.S. agencies, such as NASA, NOAA, DOE, and USDA, are responding to the science issues and goals set forth by the various international programs by funding programs and activities that best meet the roles consistent with their established charters. In this vein, NASA's ESE has put forward a list of science questions that define its research strategy for the next decade which are summarized in the next section. These questions encompass many of the USGCRP focus areas including the carbon cycle. The recommendations for NASA's carbon cycle research activities described herein outline the efforts that will result in significant contributions towards attaining the goals set out by the USGCRP carbon cycle research element. For the purposes of this document, we will refer to this planning exercise as the NASA Global Carbon Cycle Plan (GCCP). The plan reflects the cross-cutting nature of carbon research which involves closely coordinated, synergistic research and technology development in the terrestrial, atmospheric and ocean sciences and does not imply a new NASA program or that the recommendations necessarily require new funds over and above the current Earth Science Enterprise funding levels. The planning exercise simply considered what was

needed over the next ten years to address the primary science questions. While many of the recommendations can be easily accommodated within the current base program, others may not. It was left to the NASA program managers to determine which activities could be supported out of the base program, what redirection of base program activities and funding should occur, and what new funds would be required. To assess what new investments, provided either by the base program or from new funds, will be required, NASA's current assets relevant to carbon cycle research are reviewed and critical gaps are identified in this plan.

1.4 NASA Earth Science Enterprise Foci

NASA plays a major role among U.S. agencies in developing better capabilities to understand, monitor and predict the global carbon cycle through support for remote sensing, modeling and field studies. NASA's commitment to carbon cycle related science is defined in the recent NASA ESE Research Strategy document in which NASA lays out its Earth science research directions for the rest of this decade.

Five fundamental questions express the essence of NASA's Earth science program strategy:

Variability

How is the global Earth system changing?

Forcing

What are the primary forcings of the Earth system?

Response

How does the Earth system respond to natural and human-induced changes?

Consequences

What are the consequences of change in the Earth system for human civilization?

Prediction

How well can we predict the changes to the Earth system that will take place in the future?

These are further refined to a set of questions directly related to advancing understanding of the global carbon cycle.

Variability

- How is the global ocean circulation varying on interannual, decadal, and longer time scales?
- How are global ecosystems changing?

Forcing

- What trends in atmospheric constituents and solar radiation are driving global climate?
- What changes are occurring in global land cover and land use, and what are their causes?

Response

- How do ecosystems respond to and affect global environmental change and the carbon cycle?
- How can climate variations induce changes in the global ocean circulation?
- How is global sea level affected by climate change?

Consequences

- What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?

Prediction

• How well can cycling of carbon through the Earth system be modeled, and how reliable are future predictions of atmospheric concentrations of carbon dioxide and methane by these models?

Other NASA ESE science questions that are indirectly related, but highly relevant to carbon cycle science issues, are:
• How are global precipitation, evaporation, and the cycling of water changing?
• What changes are occurring in the mass of the Earth's ice cover?
• What are the effects of clouds and surface hydrologic processes on Earth's climate?
• What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?
• How are variations in local weather, precipitation, and water resources related to global climate variation?
• What are the consequences of climate and sea level changes and increased human activities on coastal regions?
• How can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?
• How well can transient climate variations be understood and predicted?
• How well can long-term climatic trends be assessed or predicted?

These questions provide the overall guiding framework for defining NASA's ESE activities, including observational capabilities, research and development programs, data management and distribution, and assessments. The NASA ESE science mandate clearly reflects NASA's important role in USGCRP's implementation of a national program to address carbon cycle science issues.

2.0 NASA'S CAPABILITIES AND CONTRIBUTIONS TO CARBON CYCLE SCIENCE

2.1 Current Programs and Cpabilities

As discussed earlier, both science and policy applications drive the information needs for terrestrial sources and sinks of atmospheric CO_2. Not only do we need to map the spatial and temporal patterns of carbon exchange, we must also understand the underlying processes in order to predict their future behavior with climate change.

Over the last three decades NASA has supported remote sensing, modeling and field studies that have contributed significantly to our current state of understanding of Earth systems science, and more specifically to the global carbon cycle. First, NASA has supported a strong research and development program across the university and NASA communities to help define the observational and information system requirements to support global change studies. This support has concentrated on furthering analysis approaches such as the one described above, and from those approaches define the necessary observational requirements and field studies needed to develop and validate the approaches. Secondly, NASA has developed the necessary instruments and space technology with which to acquire the observations. Thirdly, NASA has developed data and information systems and the knowledge of how to process, store, catalog and distribute the enormous volumes of complex interdisciplinary space and conventional data to study global processes such as:

Ocean circulation, productivity, and carbon exchange with the atmosphere

Atmospheric chemistry and greenhouse gases

Land ecosystem productivity

In addition, NASA has pioneered

National and international field campaigns (e.g. FIFE and BOREAS)
Multiple observations from the same platform (e.g. the Nimbus series)
Observations at different times during the diurnal cycle (e.g., GOES)
Cross calibration and validation of satellite sensors (e.g., SIMBIOS)
Data continuity over time (e.g., Landsat, ocean color)

More detailed summaries of NASA's current capabilities developed in its ESE programs are summarized in Appendix 2.

2.2 Critical Gaps

NASA's strategy for reducing climate change uncertainty includes improving land, ocean, and atmosphere carbon cycling models, but more importantly, new observations required to locate global sources and sinks of carbon, quantify their strengths, and understand how they depend on environmental factors that are rapidly changing. The carbon cycle models are driven and constrained by existing and new satellite and conventional observations. It is the synergy and interplay among advances in modeling, new observations of key Earth surface and atmospheric carbon and aerosol properties, and improvements in the computational capacity that supports modeling and satellite data analysis that will enable major advances in our understanding and ability to predict climate change.

As discussed in Section 1.2, the general carbon cycle investigation framework will be structured around (1) "inverse" models and (2) coupled physical and biogeochemical process models. Inverse models predict the location and strength of terrestrial and ocean surface CO_2 sources and sinks, and rely on precise observations of spatial and temporal variations in atmospheric CO_2 concentrations. Process models predict carbon transformation, storage, and the exchange rates at the atmosphere-land-ocean interfaces. Both the inverse and process modeling approaches are designed to infer regional magnitudes of net CO_2 exchange. Thus, these independently derived estimates will be compared to evaluate and test our understanding. The inverse models can be used to provide a detailed analysis of what has happened to the CO_2 that is emitted by human activities. The physical and biogeochemical process models will provide a picture of the effects of land management and land use, terrestrial ecosystem and ocean dynamics, and other environmental factors on carbon sources and sinks over time. Importantly, these models will show how future atmospheric carbon dioxide concentrations might change as a result of natural occurrences, human actions, and past and future emissions. The framework is depicted in Figure 11.

While NASA's current space assets and research programs contribute significantly to this carbon analysis framework (Table 1), new types of global observations (Figure 12) are needed to completely address the role of the carbon cycle in future climate uncertainty and include:

1) Variability in atmospheric CO_2 concentration induced by land and ocean sinks (natural and anthropogenic);
2) Stocks and rates of change in terrestrial biomass; and
3) Oceanic dissolved and particulate organic and inorganic carbon concentration (DOC, POC, DIC), photosynthesis rates, and air-sea CO_2 fluxes.

The detailed rationale and description of the new observational requirements and the observational concepts developed during the definition phase are provided in Appendix 3.

Strategic investments in the GCCP will result in the satellite capability to obtain these new observations as well as accelerate the utilization of existing satellite capabilities, e.g. Landsat. As shown in Table 1, the new data will be combined with data sets from existing satellites, the historic satellite data record, and conventional observation networks, and employed in the GCCP modeling framework. Analyses of these augmented data sets will greatly accelerate scientific understanding of the underlying physical, biological, and chemical processes of surface/atmosphere carbon exchange. The impact will be to provide input data to climate models that will reduce future climate uncertainty by reducing uncertainty in how land and ocean carbon sources and sinks will affect future atmospheric greenhouse concentrations.

Table 1 summarizes the information needed to reduce future climate uncertainty (column 1), the observations required to support the analysis framework just described (column 2), those observations enabled with existing and planned future satellites (columns 3 and 4) and new observational capabilities where additional investment is needed. Strategic investments in these new capabilities will also accelerate the utilization of existing satellite capabilities, e.g. Landsat.

Table 1. Relationship of carbon observational requirements to existing, planned and recommended ESE satellite programs.

Climate Uncertainties	**Global Observations Required**	**NASA Base Program**			**Recommended Missions**
		Historical	**EOS Era**	**Thru 2010**	
Land-atmosphere CO_2 flux and consequences for future atmospheric carbon loading	Atmospheric CO_2				Satellite CO_2 Sounders & Lidars
	Land Productivity	AVHRR	MODIS, AVHRR, SeaWiFS		
	Land Cover Type	AVHRR	Landsat, MODIS	Landsat	
	Disturbance and Recovery	Landsat	Landsat, MODIS		
	Biomass Stocks				VCL, Biomass Mission
	Biomass Change				Biomass Mission
	Precipitation		TRMM	GPM	
	Soil Moisture				

	Insolation	ERBE, GOES, SeaWiFS	ACRIMsat, SeaWiFS, MODIS	VIIRS	Ocean Carbon Mission
Land-atmosphere CH_4 flux	CH_4 concentration		MOPITT, HIRDLS, TES		
Air-Sea CO_2 flux (Solubility & Biological Pumps)	Wind speed		Quikscat		
	Sea Surface Temperature	AVHRR	AVHRR, MODIS	VIIRS	
	Salinity				
	Chlorophyll	CZCS, SeaWiFS	SeaWiFS, MODIS	VIIRS	Ocean Carbon Mission
	Productivity	CZCS, SeaWiFS	SeaWiFS, MODIS	VIIRS	Ocean Carbon Mission
	Organic Carbon (Particulate & Dissolved)				Ocean Carbon Mission
	Inorganic Carbon				

To fully utilize the new observational capability new investment will be needed in certain key modeling elements of the carbon analysis framework (see Appendix 3 for more detail). For example, 3D atmospheric modeling of CO_2 provides the basic framework to analyze existing and proposed measurement network data and satellite remote sensing of CO_2 distributions. Acceleration of the development of numerical simulation models of atmospheric CO_2 transport (and other tracers such as N_2O, CH_4, and biomass burning tracers) to more precisely determine their atmospheric distribution and thus more reliably trace their original sources is needed.

The fate of anthropogenic carbon is also strongly influenced by the terrestrial biosphere. Recent efforts have shown the tight coupling between the atmosphere and dynamic vegetation processes on interannual and interdecadal time scales. Accelerated efforts are needed to develop coupled atmosphere-ocean-land-vegetation models to provide a comprehensive understanding of these processes and improve the prediction of future trends in atmospheric CO_2 concentrations.

On seasonal-to-interdecadal time scales, ocean general circulation models (OGCM) need to be coupled with ocean biogeochemical/optical models (OBOM), and atmosphere models. Land surface hydrological models need to be enhanced with the carbon components from terrestrial ecological models and coupled with the atmospheric general circulation models (AGCMs). On decadal to climate change time scales, terrestrial ecological models need to be linked with OBOM/OGCM's and climate models of the Earth system. This sequence of coupled

models linked to satellite data fields, via data assimilation, will require substantial development time, will result in a satellite data assimilation-forecast model that can evaluate and predict changes in anthropogenic forcing of carbon related processes with near-term changes in carbon cycling, which may have important effects on climate and weather systems.

Acceleration of efforts to develop improved data assimilation techniques for both physical and biogeochemical data to improve model predictions is also needed. Assimilation of remote sensing data into coupled models can constrain the models from following erroneous trends and, therefore, improve their representativeness. This combination of modeling and data assimilation can produce enhanced data sets by filling in gaps and providing vertical resolution that is often unattainable from remote sensing data alone. It can provide information on fluxes, rather than static pools or states, which are difficult to obtain from data alone. Finally, data assimilation facilitates the capability for short-term forecasting. By constraining the models to the data, the models can provide future predictions with greatly improved accuracy. The ability of the assimilation system to forecast, of course, depends on the stability and accuracy of the model, the accuracy of the input data fields, and the rate at which the natural environment changes. This acceleration of development activities can build on existing programs such as the Data Assimilation Office (DAO) and the NASA Seasonal-to-Interannual Prediction Program (NSIPP). Also, most data assimilation development has focused on physical systems, but biogeochemical systems may require methods. Remote sensing data assimilation requires accurate, complex, representative coupled models, but also an intimate knowledge of the characteristics, and limitations, of remote sensing data. Because much of our current knowledge lies within the NASA extended community, it is considered important that data assimilation be a major component of the GCCP.

Not directly evident as a part of the carbon analyis framework in Figure 11 are observing system simulation experiments (OSSEs). OSSEs are a tool to assess the capability and feasibility of utilizing remote sensing technology to sample an Earth system parameter. Typically a simulated field representing a variable in question is created. This may be derived from data sets, simulation models, or a combination. The level of complexity and realism depends on the nature of the questions posed and the inherent properties of the variable under investigation. Then simulated aircraft tracks or satellite orbits are propagated over the simulated field to understand how well the observation technology samples the variable. This can help define orbit selection as well as refine our estimates of measurement accuracy. Thus, OSSE's are an extremely valuable methodology for remote sensing applications and mission development. OSSE's were used extensively in the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project before launch, and included virtually all phases of the mission, from command and control, to data acquisition, to data processing and quality control. Many pre-launch engineering, orbit, data processing, navigation, quality control, and operations issues were successfully resolved before launch using this methodology, and contributed to the success of the mission. OSSE's are considered essential to the GCCP.

2.3 Why a NASA Global Carbon Cycle Plan?

The mission of NASA's ESE is to develop a scientific understanding of the Earth system and its response to natural and human-induced changes to enable improved prediction of climate, weather, and natural hazards for present and future generations. The purpose of the GCCP is to provide strategic additional investments to quantify and understand the Earth's carbon cycle, accelerating the reduction of key uncertainties in the causes, magnitude, and direction of climate

change and the availability of this information to decision-makers. While NASA's current space assets constitute a formidable capability with which to study the earth's carbon cycle, additional new observations and improved process models are needed.

NASA programs and assets are critical to implementing the carbon strategy, including its Earth observing systems, high-end computing capabilities, its data distribution systems and its interdisciplinary science teams. NASA has the capability and programmatic infrastructure to develop the new in situ, aircraft, and satellite observational technologies required, such as lasers, microwave sensors and space-based antennas, and can be executed under the Small Business Innovation Research (SBIR), Advanced Technology Initiatives Program (ATIP), Instrument Incubator Program (IIP), New Millenium Program (NMP), and Earth System Science Pathfinder (ESSP) program, for example. NASA has a recognized role in combining coupled land, ocean and atmosphere models, satellite observations and analyses. Global carbon cycle models incorporate into an integrated whole, myriad linked hypotheses concerning the generation, storage and transport of carbon, water, and energy through the various systems. A new NASA carbon cycle research and technology development plan will foster the further development and coupling of these models and develop a synthesis of the historic and ongoing satellite observation stream with which to study the global carbon cycle.

Finally, a new NASA GCCP will foster the cooperation of national and international partners to ensure the continuity of key environmental measurements by promoting the convergence of operational observation requirements and measurement standards with the ESE research data requirements. Through a comprehensive outreach component, the GCCP will help assure that the advances in knowledge about the Earth system will achieve maximum societal benefit through their application by and communication to stakeholders in state and local governments, industry, and the general public.

The NASA ESE efforts that will be accelerated under the GCCP are:

1) The development of new satellite capability to fill missing observational gaps in the carbon analysis framework: atmospheric CO_2, terrestrial biomass, and ocean carbon.
2) Acceleration of the development of certain key modeling elements in the carbon analysis framework: Numerical atmospheric tracer models, enhanced terrestrial and ocean ecosystem carbon cycling models, and coupled land, ocean and atmospheric models for climate prediction.

The new baseline NASA ESE efforts that will be accelerated under the GCCP are:

1) increased participation in the proposed interagency-supported North American Carbon Program (NACP), the impact of which will be to greatly reduce uncertainty in the location, and strength of the North American sink and the underlying processes, and thus reduce uncertainty in how this and other terrestrial and ocean sinks will affect climate change as changing environmental and human factors affect them,
2) accelerated production of a global land cover change map that can resolve and quantify, for the first time, the amount and rate of ecosystem disturbance from natural causes and human activity and their impact on atmospheric greenhouse gases, and
3) participation in other terrestrial and ocean campaigns, e.g., "hot spots" where climate is changing rapidly or atmospheric carbon fluxes are believed to be large (coastal oceans, the southern oceans, Eurasia, and the tropics).

3.0 SCIENCE AND TECHNOLOGY ROADMAPS

3.1 Approach, Guidelines and Definition Process

In April of 2000, NASA Headquarters charged the Goddard Space Flight Center (GSFC) to lead a team consisting of the science community, NASA Headquarters representatives, NASA center representatives, and other agency representatives, to develop a NASA-wide GCCP. The plan would need to define a science and technical roadmap to focus NASA's current space assets, carbon cycle science programs, and facilities on improving our understanding of the global carbon cycle and provide information products supporting decision makers and the user community. The plan would also need to identify, cost and prioritize any new science programs, space missions or facilities required. The plan would define program success criteria, that is, performance metrics against which to gauge the future progress and accomplishments of the effort in terms of its stated goals. Finally, the plan would contain an approach for implementing the proposed effort, including a management framework defining the relationship between senior management at NASA Headquarters, a program office and individual flight project management offices.

The plan definition process formally began in the fall of 2000 with the selection of a Science Working Group and the announcement of the process to define the GCCP. GSFC and Wallops Flight Facility (WFF) scientists worked with the other organizations participating in the definition phase (see Figure 13). These included: (1) the NASA center representatives (Jet Propulsion Laboratory (JPL), Ames Research Center (ARC), Langley Research Center (LaRC), Marshall Space Flight Center (MSFC), Kennedy Space Center (KSC), and Stennis Space Center (SSC); (2) NASA Headquarters program office representatives (including managers of relevant programs in Codes Y, S, and U); (3) a Science Working Group (SWG) and, (4) the carbon cycle IWG. The GSFC team, assisted by these other groups, conducted the necessary studies to define new science programs, facilities and mission requirements and costs. The GSFC team consisted of personnel from GSFC Codes 910, 920, 930, 940 and 970 as well as representatives from the project formulation office within Code 740.

The proposal definition process itself consisted of three workshops and a number of GSFC studies to investigate mission concept feasibility (Figure 14). The workshops consisted of joint plenary sessions and separate science discipline break-out discussions. Each discipline break-out had a discussion leader and a rapporteur. After each workshop, the discussion leaders submitted summaries which are reproduced in Appendix 5. Workshop attendees are listed in Appendix 6.

The focus of the first workshop held at the GSFC January 9 - 11 2001, was to define the science questions the NASA GCCP would need to address, the information products that would need to be produced, the performance metrics that such products would need to satisfy and what NASA's potential new contributions would be in the context of other agency efforts. It was agreed then to accept the science questions that had been articulated in "A Carbon Cycle Plan" by S. Wofsy and J. Sarmiento, published in 2000 under the auspices of the USGCRP. Information products in the broadest terms, would consist of locating and quantifying the magnitudes of global carbon sources and sinks as well as the remote sensing products that support such assessments as shown in Table 1. Part of the planning effort would be to use the GCCP modeling framework to better define just how accurate such products must be to improve existing information and to make useful assessments in support of US policy goals and thus the specific nature of the performance metrics. A major result of the first workshop was a community consensus as to the missing observations required to answer the science questions

posed. These were identified as observations of high-spatial and temporal resolution atmospheric CO_2, terrestrial biomass and biomass change, ocean surface layer organic and inorganic carbon, air-sea CO_2 fluxes, and global land cover and land cover change products from Landsat. In addition, preliminary observational and technology approaches (observational requirements and instrument types) were defined for more detailed study between the first and second workshop.

The focus of the second workshop (March 20-22, 2001) was to define a NASA science and technology roadmap required to address the science questions in the context of existing agency capabilities. This roadmap is the set and sequence of activities and resources that would be required to develop the new observations and associated modeling and field programs needed to address the science questions, produce the information products and satisfy the performance metrics laid out in the first workshop. Also, as part of the preparation for the second workshop, the new measurements identified in the first workshop were linked with potential missions. These mission concepts were developed in greater detail and paired with appropriate spacecraft and launch vehicles in the Integrated Mission Design Center (IMDC) at GSFC. IMDC studies included an aerosol polarimeter, a CO_2 lidar, and an advanced land biomass lidar. This process examined the various subsystems as well and sought to identify any technology challenges by subsystem and for the mission as a whole. The results of these studies could then be used as a basis for costing potential missions with the assistance of the Resource Analysis Office (RAO) in preparation for the third workshop (May 2-4, 2001). This information could then serve as the basis for an informed prioritization of the candidate science activities, both individually and in synergistic combinations.

The third workshop consisted of reviewing a draft GCCP, the science and technology roadmaps (activities, activity relationships, missions, schedules, resource requirements, etc.), and prioritizing missions and activities. It was agreed at the third workshop to initiate a series of telecons involving the carbon planning team to put together a presentation to the NASA Associate Administrator of the Office of Earth Sciences, Dr. Ghassem Asrar, and his staff. The formal presentation (Appendix 7) was on June 19, 2001, shortly after the President's call for climate research and technology initiatives. The science and technology roadmaps will be summarized in the following sections.

3.2 Science Roadmap

As discussed previously, coupled land, ocean and atmospheric carbon cycling models, driven and constrained by satellite and conventional observations will form the carbon analysis framework of the GCCP. The general modeling framework will be structured around: (1) inversion models that exploit spatial and temporal variations in atmospheric CO_2 concentrations to track CO_2 transport from the land and ocean surface through the atmosphere, and (2) physical and biological process models that predict the exchange rates of CO_2 between the atmosphere's interface with land and ocean surfaces and the carbon transformations that occur within each domain. Both modeling techniques are designed to infer regional magnitudes of net CO_2 exchange. They can be intercompared, and thus provide insight into (1) what has happened to the CO_2 that has already been emitted by human activities, (2) how land management and land use, terrestrial and ocean dynamics, and other factors affect carbon sources and sinks over time and, (3) how future atmospheric carbon dioxide concentrations might change as a result of environmental changes, human actions and past and future emissions. These three endeavors are in essence the goals of the USGCRP Carbon Plan. Figure 15 provides an overview of the science roadmap that has been developed and shows the activity blocks and timing, i.e. the program to

address the USGCRP science questions and goals and the research and observational requirements that derive from them. The activities, the horizontal bars, fall into three general groups. The top three bars represent either current space observations or activities to develop the new observational capabilities required. The second group, the next five activity bars, are those activities required to convert the satellite radiances into observational parameters and the analysis and modeling capabilities, along with these observations, needed to address the questions and perform the necessary assessments.

In particular, a North American field campaign is the first phase of a longer term NACP and will be central to developing, calibrating and validating advanced sensor techniques and algorithms. It is discussed in more detail in the next section. The last four bars are those activities required to develop coupled physical-biogeochemical models with satellite and conventional data assimilation capabilities for conducting regional and global analyses, providing answers to the science questions and enabling projections and assessments. The top activity bar of Figure 15, "Current/Planned Space Assets", expresses the assumption that the global data products from Terra, SeaWiFS and other currently operational sensors will be available from NASA's base program to the carbon cycle program. For Landsat data, however, a new requirement was defined, and that is to accelerate the analysis of global carbon-specific data products from Landsat, including land cover and land cover change maps and the production of global 30 meter land cover disturbance maps. This would require the automated classification of the global ortho-rectified Landsat data set being assembled by Earth Satellite Corporation from the 70's, the 90's and 2000. This activity would provide global information on natural and anthropogenic disturbance in each decade. From these maps, rates of disturbance, cause of disturbance, and age distribution would be produced at 30 meters and aggregated to appropriate scales (e.g. 10 km) for global carbon analyses. This data set will be key to addressing changes in ecosystem carbon stocks.

As shown in the third activity bar from the bottom, labeled "Data Synthesis", all relevant satellite data products, as well as other data necessary to the carbon analysis framework, will need to be synthesized into global data sets, with a common grid and format, and provided to the GCCP science community for analysis.

New missions would occur no sooner than 2007, given a 5-year formulation cycle. However, if the ongoing NASA ESSP process were to select a carbon dioxide observation mission in mid-calendar 2001, a carbon mission could occur as early as 2006.

An important part of the GCCP is the model development activity that will focus on improved utilization of satellite data. Ecosystem land and ocean process models need significant development to properly utilize the new data sets that remote sensing satellites will make available. For example, we need a better understanding of the carbon consequences of disturbance, higher spatial resolution inversion models, improved inversion techniques, etc.

NASA participation in the field campaigns would focus on process model development, satellite sensor calibration, algorithm development, and satellite product validation. The GCCP would also include accelerated activities in the NACP, e.g., a field campaign in 2004 and 2005, and subsequent studies of tropical areas, Eurasia, and the southern oceans.

The science roadmap in Figure 15 is a summary of much more detailed roadmaps that were developed by the GSFC atmosphere, ocean, and land groups in collaboration with the GCCP team during the workshops. These more detailed roadmaps are displayed and described in Section 3.4.3. The roadmap is consistent with the research goals and objectives established by

the NASA ESE and the USGCRP, but expands and accelerates particular, key activities that will substantially reduce uncertainties about future climate change.

3.3 Technology Roadmap

An extensive evaluation of the technology readiness for each proposed observational concept has already been undertaken along with an assessment of observational feasibility. Figure 16 summarizes the mission concepts proposed for the GCCP and studied in detail during the proposal definition phase. Appendix 4 contains detailed descriptions of the observational requirements and proposed instrument and mission concepts. These assessments have shown that reaching the stage of technological readiness required for an on-orbit demonstration of the concepts for the new measurements will need a careful, stepwise progression of technology, algorithm development (for extracting the necessary observations), and validation. Some of the capabilities (e.g. the CO_2 lidar) are in the laboratory demonstration phase, while others, such as the Ocean Carbon Mission, have had instruments of similar capability or complexity (passive optical) demonstrated on orbit. Regardless, all new GCCP space observation technology developments will be supported, when it is deemed necessary and useful, by laboratory, field, and aircraft instrument demonstrations and intensive field program validation. Before any observational concept is deemed ready for space demonstration, it will be subjected to a step-wise series of rigorous tests and evaluations. It is anticipated that the earliest any of the new observational capabilities could be deployed would be at least three years for very mature technologies, e.g., Ocean Carbon Mission, and five years or longer for less mature ones.

Given these realities, it would be premature at this stage in the planning to specify the timing for the new GCCP capabilities or launch schedules. However, for planning purposes Figure 17 provides a "notional" set of mission schedules and the requisite technology development "wedges" leading up to the space-based deployments of science observational missions and/or demonstration missions. A launch date of 2005 is shown for a first vegetation canopy height lidar (VCL) mission. Late 2005 is possible only because development of VCL technology has been pursued over the past few years under the ESSP program. As discussed in the previous section, to accurately measure the rate of biomass recovery will require follow-on measurements to assess change and, possibly, two measurement approaches: one for low density biomass and one for high density biomass. VCL will be the first of these biomass sensors. It will take about 18 months for VCL to record the first global biomass survey, improving the accuracy of our knowledge of land biomass by a factor of 20 or more. An advanced high density biomass mission is tentatively scheduled five years following VCL, provided that VCL is successful, and will map the changes in global biomass that have occurred in the intervening period. The advanced high density biomass satellite will incorporate some technology changes to extend the range of ecosystems observable with the single-frequency lidar flown aboard VCL, particularly the northern, high-latitude ecosystems that are important players in the global carbon cycle. A series of aircraft missions beginning in 2003 will explore advanced biomass technologies (high and low density), including dual-frequency lidars, hyperspectral radiometers, and radar. The biomass change design will be based on the results of these experiments and what is learned from VCL.

It is important to obtain improved estimates of spatial and temporal variability of atmospheric CO_2 as soon as possible. It appears that such observations can be obtained most quickly with a pathfinder CO_2 sounder, based on a passive sensor technology. With a 2003 GCCP start, the pathfinder could be ready for demonstration in five years, i.e., 2008. A mission

lifetime of 5 years is proposed to observe useful interannual variations in land and ocean sinks and sources to correlate with climate variations induced by phenomena such as the El Niño-Southern Oscillation (ENSO). An advanced CO_2 lidar sounder is proposed to overlap one year with the pathfinder. We assume that the greater resolution and higher accuracy of a lidar approach will be needed. In comparison to the pathfinder, the advanced sounder will provide CO_2 information closer to the Earth's surface, at a different time of the day, and with less interference from clouds. The lidar, unlike the passive sounder that relies on the sun as its illumination source, will be able to obtain CO_2 concentrations nearer the Earth's surface, where the surface-induced CO_2 signal is stronger. In addition, because it provides its own illumination, the lidar can measure column CO_2 near dawn and dusk when column CO_2 measurements are easier to relate to surface-atmosphere exchange. Finally, cloud interference is much less at dawn and dusk, thus CO_2 concentrations could be obtained on a more frequent basis. Results from both the passive and active aircraft CO_2 instruments as well as the CO_2 pathfinder will be used to decide if the lidar is justified in terms of how accurately and how finely regional sources and sinks can be located.

New ocean observations would be possible in 2009 and 2010, one focusing on global carbon exchange with the open ocean, the Ocean Carbon Mission described earlier, and the second, a combined coastal ocean-land mission based on high resolution passive radiometry, to observe low density terrestrial biomass and carbon uptake at the land-ocean interface, a region long overlooked in quantifying carbon exchange. The coastal ocean observations are consistent (time of day, resolution, etc.) with those for observing low terrestrial biomass density, where lidar and radar technology do not perform well. To extend the range of global terrestrial biomass observations to medium and high density biomass regions and dramatically improve the sampling density, a high density biomass mission is envisioned for 2011. This is a logical follow-on to the VCL and a low density biomass mission and would incorporate the lessons learned to improve our ability to obtain accurate measures of biomass and biomass change over a complete range of global ecosystems.

Observational accuracy requirements are stringent and will require investments in both technology, and research and development. A comprehensive field program will be conducted to develop satellite observation algorithms, calibrate the new sensors, and validate their data products. The GCCP will leverage off the programs already being conducted by other federal agencies which can provide validation data (e.g., the NOAA CO_2 flask network, the USFS forest inventory), shipboard measurement opportunities, joint model development and evaluation activities, and others. Advanced analysis capabilities and models will be developed to take maximum advantage of the new observations. Models as they currently exist, must be improved to utilize the full power, resolution, and detail of the new observations. The GCCP will employ both observations and modeling to optimize predictions of carbon cycle and climate processes and responses.

3.4 Program Phasing

The major thrusts of the first five-year phase of the GCCP (2003-2008) is the participation in the NACP and the development and delivery of the new climate observational technology and infrastructure and the demonstration of these technologies in the NACP. To reduce risk, aircraft-prototype instruments for the less mature CO_2 and terrestrial biomass measurement technologies will be developed and flown over intensively studied sites, selected in conjunction with the NACP. Data from these flights, along with the field infrastructure for

validation and reanalysis, and the synthesis of the existing record of satellite data will contribute directly to the reduction of uncertainty in the strength of the North American sink and to the determination of the underlying processes.

In the second five years of the GCCP (2008-2012), the new observational capabilities can rapidly come on-line as they are deemed ready and necessary. New instruments can be launched at regular intervals with the most mature, and scientifically compelling, measurements going first. Priorities will be set in accordance with the ESE science and implementation priority criteria.

3.4.1 Phase 1 (Years 1-5)

During the first five years, activities will center on the following seven activities:

1) NASA participation in the NACP
2) Analysis of Landsat data for the carbon effects of land cover change and disturbance
3) Global carbon data synthesis using existing and new data sets
4) Implementation of key technology development strategies, e.g., laser systems for the advanced CO_2 and high density biomass missions
5) Fabrication, testing, and deployment of new ground-based and aircraft instruments
6) Advanced planning for all recommended missions and flight hardware fabrication for "high technology readiness (HTR)" missions (Pathfinder CO_2, Ocean Carbon)
7) Continuity of systematic observations of ocean color adequate to address climate change initiative goals

Each of the seven activities is described below.

1) NASA Participation in the NACP

The NACP focuses on the land area of the United States, adjacent areas of Mexico and Canada, and adjacent oceans to define regionally-resolved sources and sinks for CO_2 and other important carbon gases (CH_4, CO, selected non-methane hydrocarbons (NMHCs)). The NACP will provide quantitative understanding of the uptake or release of carbon attributable to natural and human activity. It will require multi-agency investments in a network of CO_2 flux towers, some of which are already in existence, a series of regional aircraft surveys of atmospheric CO_2, simultaneous measurements of air-sea CO_2 fluxes in both the Atlantic and Pacific, and extensive forest, cropland, and soil inventory data. Also, the terrestrial flux of carbon via fresh water discharge into the coastal oceans will be estimated and its fate established (i.e., transport to the deep ocean, deposition to continental shelf sediments, or release back to the atmosphere) in this attempt to close the North American carbon budget. NASA will contribute to this program in collaboration with most of the USGCRP agencies.

The major field studies and airborne campaigns for the NACP are currently proposed for 2004-2006 in order to deliver critically needed information on North America's role in the global carbon budget. NASA plans to contribute aircraft platforms, sensors, and flight hours; custom satellite data analyses; new in situ and airborne sensors; and advanced carbon modeling and data assimilation to the NACP. All but the new sensors and advanced data assimilation could be achieved within NASA's existing research and analysis budget if the NACP field and airborne studies were to occur in 2005-2008. However, commitments to existing field programs and airborne campaigns and their post-mission analysis phases make it impossible to meet the earlier schedule for the NACP without augmented funding. Additional resources will allow NASA to

accelerate its participation in the NACP and help the multi-agency group deliver a North American carbon source/sink analysis within five years.

Furthermore, new funding requested through the GCCP will enable NASA to take advantage of the NACP to develop and evaluate remote sensing technology and new measurement capabilities for carbon cycle components and aerosols. NASA will develop and/or deploy in situ and airborne sensors, including alternative technological approaches for a needed measurement, over well-characterized NACP study sites to evaluate each sensors' ability to quantitatively measure atmospheric CO_2, biomass, or coastal ocean contributions to CO_2 dynamics. Additionally, those sensors that check out will provide valuable and unique new data sets for the NACP. NASA, through its base program, will help in ensuring that the new data sets acquired through the NACP are generally available and archived in appropriate Earth science data archives.

In preparation for the field campaign component of this program, a number of ground based passive spectrometers will be developed and built for estimating tropospheric CO_2 concentrations. Ultimately, a global network of these instruments could be used for satellite validation, assuming they can be made to be sufficiently accurate. A global network of sun photometers for satellite aerosol validation has already been established and could be augmented with these CO_2 radiometers. These measurements combined with the flux tower and aircraft vertical profile data provided by NASA and other federal agencies will be used to evaluate CO_2 retrievals from the Aqua/Atmospheric Infrared Sounder (AIRS) instrument discussed previously. Methane measurements that will be acquired from Terra/Measurements of Pollution in the Troposphere (MOPITT) and Aura/Tropospheric Emission Spectrometer (TES), and that are already provided for in NASA's base program, will be used as well. NASA's coastal ocean contribution to the NACP will include not only air-sea CO_2 flux estimates based on satellite ocean color, temperature and wind estimates, but will also focus on the development of satellite algorithms for estimating dissolved organic and particulate carbon. These require a variety of in situ measurements of chemical, biological, and optical properties. Because these relationships may be regional due to the biological and geological differences in drainage basins, algorithm and process model development field studies are envisioned for six different regimes (Gulf of Maine, Middle Atlantic Bight, South Atlantic Bight, Mississippi Delta, Pacific Northwest, and Bering Sea). Augmented funding will be required for the ocean cruises needed to characterize these six coastal regimes. Data from SeaWiFS and the Moderate Resolution Imaging Spectroradiometer (MODIS) will be used for extrapolating the field measurements across the entire North American continental shelf. To augment the standard shipboard measurements, new aircraft instrument concepts to be developed under the GCCP, primarily lidar systems, will be evaluated and considered for measuring the profiles of particulate and bicarbonate concentration.

2) Analysis of Landsat data for the carbon effects of land cover change and disturbance

NASA's base program-supported analysis of the large historical data set accumulated from the series of Landsat satellites for global land cover and land cover change will be augmented to develop more automated processing algorithms to reduce data analysis costs and to assess the effects of land use change and natural variability on carbon fluxes over the past 3 decades. In addition, augmented funding will accelerate analyses of land cover change in North America and its impacts on carbon dynamics so that these results are available for timely use in the NACP. Augmented funding will also accelerate processing and permit management of the nearly 7000 Landsat scenes comprising each 30 meter resolution global land cover data set.

3) Global carbon data synthesis using existing and new data sets

In order for researchers to most effectively utilize the variety of satellite, field, and model data collected for the GCCP, an systematic approach for organizing, formatting, and distributing these data must be included in the program design. The effort builds on existing systems such as the SeaWiFS-SIMBIOS bio-optical field data archive and the EOS Distributed Active Archive Centers (DAACs).

4) Implementation of key technology development strategies, e.g., laser systems for the advanced CO_2 and high density biomass missions

In order to achieve new measurement capabilities in time to influence climate change policy decisions, certain technology development activities need to be initiated and/or accelerated as soon as possible. Each of the recommended measurements and potential implementation options has been reviewed for instrument, telemetry, and spacecraft subsystem technology readiness levels. The desired accuracy and precision required for CO_2 and land biomass measurements appear to demand laser technology advances beyond those of the current satellite laser instruments, e.g., near-infrared lasers. Other areas of development are onboard data processing, high data rate collection and telemetry, and precision geolocation. NASA has a number of technology programs that provide mechanisms for pursuing the development activities, e.g., SBIR, ATIP, IIP, and NMP. These programs are broad in scope, so some, but not all, of the required resources for GCCP technology development will be provided under these programs. The strategy will be to work with these program offices to coordinate GCCP solicitations, selections, and funding. Experience with EO-1/Hyperion and vegetation canopy lidar (when available) will help clarify some of the technology issues for hyperspectral and lidar measurements of terrestrial above-ground biomass.

5) Fabrication, testing, and deployment of new ground-based and aircraft instruments

The instruments being considered include the ground-based passive CO_2 radiometers, the ocean particulate lidar (profiles of particle concentrations and possibly mixed layer depth), and an ocean bicarbonate (a major component of the dissolved inorganic carbon pool) lidar. Development of a shipboard version of the ocean particulate lidar is underway. Also, aircraft prototypes of some of the recommended satellite sensors may need to be built, particularly for the CO_2 missions and possibly for terrestrial biomass. These will be used to support the NACP. An aircraft version of the aerosol polarimeter already exists and would be used.

6) Advanced planning for all recommended mission and flight hardware fabrication for "high technology readiness (HTR)" missions (Pathfinder CO_2, Ocean Carbon)

Missions will be competed. Prior to the solicitation and competition, measurement specifications (accuracy, coverage, resolution) and preliminary system studies (power, navigation, weight, thermal control, spacecraft, launch vehicle) would need to be completed to establish potential cost and guide the solicitation for proposals. The HTR missions are categorized as low risk and could be the first missions to be launched, if they meet minimum science observational requirements, because they are based on existing passive radiometry technologies. The pathfinder CO_2 mission would provide estimates of total column CO_2 without information on vertical distribution.

7) **Continuity of systematic observations of ocean color adequate to address carbon cycle research goals**

The GCCP recommends the continuation of the SeaWiFS data buy. The SeaWiFS extended data set guarantees the continuation of the longest global ocean biology time series (presently four years). The present data buy contract continues until December 31, 2002. This data set will allow evaluations of interannual biological variability due to the ENSO, the North Atlantic Oscillation, and other global scale climate phenomena. The costs associated with the SeaWiFS extension were not included in the GCCP cost analysis.

3.4.2 Phase 2 (Years 6 - 10)

1) **Advanced mission hardware fabrication and testing (Low Density Biomass/Coastal Ocean, High Density Biomass, Advanced CO_2)**

It is expected that missions to acquire these observations will occur late in the GCCP because significant technology development will be needed in advance. The low density biomass/coastal ocean measurements may be an exception depending on the measurement specifications (data rate in particular). The current concept for this mission is hyperspectral, but a simpler design may be possible. The high spatial resolution for estuarine systems is consistent with that required for terrestrial studies. Concepts for the high density biomass include lidars, synthetic aperture radars, passive radiometers for bidirectional reflectance (BRDF), and other sensors sensitive to vegetation structure, probably in some combination. The Advanced CO_2 mission is expected to be a lidar system which can operate at dawn and dusk resulting in the ability to acquire a substantially different vegetation-atmosphere CO_2 signal than passive measurements, and when cloud cover interference is reduced. These concepts are discussed in detail in Appendix 4.

2) **Launch of new missions and post-launch validation and analysis programs**

Unless some of the required measurements are selected under the present ESSP solicitation, it is not expected that new observation capabilities will be feasible before 2007 (except for a possible flight of the already approved VCL) because of the 5-year lead time required to design, build, and launch a satellite. However, a number of mission scenarios have been developed and costed based on possible ESSP selections and a successful vegetation canopy height mission.

3) **Southern Ocean source/sink field program(s)**

One of the greatest current uncertainties in estimating the oceanic carbon sequestration is the Southern Ocean (i.e., the ocean south of 30°S). Historically, sampling has been very sparse due to the difficulty and expense of data collection. After the initial field campaigns for the NACP are completed, a field experiment in the Southern Ocean is being considered. Presumably, there will be CO_2 and ocean carbon missions on orbit by that time, as well as new mooring and buoy-based measurement systems, e.g., the Argo array of profiling drifters.

3.4.3 Science Discipline Activity Schedules

As a result of the discussions during the workshops, as summarized in Appendix 5, and at GSFC between workshops, schedules of activities designed to address the science objectives were developed and costed by each of the discipline groups. These activities were generally organized into (1) field campaigns (e.g., NACP, Southern Ocean), (2) algorithm development

and calibration/validation, (e.g., ocean dissolved and particulate organic matter), (3) in situ instrument technology development and fabrication (e.g., ground-based CO_2 radiometers), (4) data processing and synthesis (e.g., Landsat land cover products), (5) model development, data assimilation, and observational system simulations (e.g., a coupled land, ocean, atmosphere physical-biogeochemical model) and (6) investigations addressing the carbon cycle science questions using the data and model products derived from activities 1-5. The discipline plans were organized and timed to be mutually supportive as were the budgets (outlined in a separate document). The schedules are depicted in Figures 18-20.

3.5 Technology Development and Mission Cost Estimation

Space and aircraft mission costs were developed by the project formulation and systems engineering team utilizing existing data bases and cost estimating relationships. A full life cycle costing (LCC) methodology was adopted for all mission costs. The term LCC refers to the total cost for all mission elements (launch, flight, and ground) required to formulate, implement, and operate each mission and also deliver the required data to the science and user communities. For purposes of costing, the GCCP was treated as a stand-alone program with its own funding for mission-specific technology. Other programmatic assumptions included an open data policy with traditional roles and responsibilities for NASA Headquarters, GSFC, other NASA centers, government agencies, universities, and industry.

Initial cost estimates were prepared for a baseline set of five missions and several options. These costs are outlined in detail in a separate companion document. The baseline set included a pathfinder atmospheric CO_2 mission, an ocean carbon mission like SeaWiFS, but with better spatial resolution and additional UV and fluorescence bands, a low density biomass/coastal ocean mission, a high density biomass mission consisting of a radar and lidar combination, and an advanced atmospheric CO_2 (lidar) mission. These missions were intended to be generic and to serve only as a basis for providing costs to scope the program. It is recognized that a specific implementation technique for making each critical carbon cycle measurement can only be determined after a concerted concept definition and formulation phase as directed by NASA program guideline 700-PG-7120.5A. Nevertheless, for purposes of program budget planning, it was necessary to develop very basic concepts with associated mass, power, and data rate estimates so that existing cost estimating relationships could be employed. Competition and the peer review processes will determine what mission concept is ultimately selected.

A mission cost template was developed that included the following elements of cost: technology development, preformulation, formulation, project management, instrument design and development, spacecraft design and development, mission systems integration and testing, launch vehicle, ground and data system accommodations, mission operations and data analysis, post-launch calibration and validation, contingency, and fee. The costs for preformulation, formulation, and project management were based on estimates for expected staff salaries and definition studies. Instrument design and development costs for most missions were generated by the GSFC Resource Analysis Office (RAO) based on information provided by the study team and using a multi-instrument cost model (MICM) that was constructed from a data base of similar instruments. The lower limit assumed a three-year mission and a three-year implementation phase. The upper limit assumed a five-year mission and four-year implementation phase. All instruments were costed in the protoflight mode with an engineering model included for the higher risk laser/lidar systems. The cost of the P-band synthetic aperture radar for the high density biomass mission was taken from previous Earth science mission

studies. Technology development was also estimated by RAO considering the effort required to bring an instrument from its current TRL to a level of 6 by the time of mission approval (implementation phase). A spacecraft cost range was then provided by the GSFC Rapid Spacecraft Development Office (RSDO) after an analysis was performed to ensure that there were candidate buses in their catalog that could accommodate the proposed scientific instruments. Launch vehicle/service costs were supplied by the GSFC Access To Space (ATS) group. Ground system development, mission operations and data analyses were estimated by the GSFC Networks and Mission Services Division. Post-launch calibration and validation costs were provided by the science team. Life cycle costs and cost profiles were then compiled for each mission in the baseline set.

Four optional mission sequences, identified in the table below, were also considered during the GCCP study. These options included a reduced mission set as well as modifications to the proposed flight program and adjustments to cost that could be made as a result of a successful launch of VCL in the near term and/or an ESSP mission selection favorable to carbon cycle science. The missions are listed in anticipated launch sequence for each option.

Option 1: Reduced Mission Set and No VCL Launch
Pathfinder Atmospheric CO_2/Ocean Carbon
High Density Biomass
Advanced Atmospheric CO_2

Option 2: Successful VCL Launch
Pathfinder Atmospheric CO_2/Ocean Carbon
Advanced Atmospheric CO_2
High Density Biomass

Option 3: Early ESSP Carbon Mission Selection and No VCL Launch
Pathfinder Atmospheric CO_2 (ESSP)
Ocean Carbon
High Density Biomass
Advanced Atmospheric CO_2

Option 4: Early ESSP Carbon Mission Selection and Successful VCL Launch
Pathfinder Atmospheric CO_2 (ESSP)
Ocean Carbon
Advanced Atmospheric CO_2
High Density Biomass

Costs for aircraft missions were estimated based on discussions with various scientists and included missions in support of the pathfinder and advanced atmospheric CO_2 measurements as well as the low and high density biomass imaging missions. In addition, there were two stand-alone aircraft missions, not associated with a space mission: an ocean bicarbonate lidar and an ocean particulate lidar. Costs presented are for initial demonstration of instruments dedicated only to aircraft operations and for demonstrating the performance of an aircraft version of an intended spaceborne instrument. Aircraft flights in support of post-launch calibration/validation,

spacecraft underflight, and extended science field campaigns are included separately in the science discipline budgets.

Only new aircraft instruments and accompanying integration and test flights were estimated in this section. Aircraft instrument costs were estimated by selecting an aircraft instrument that could represent any of the known candidates for making the measurement. Actual instruments for field campaigns, and calibration/validation of carbon cycle space instruments after launch will be determined at the time of deployment. The estimates for three classes of aircraft missions: measurement validation of the carbon cycle space instrument and future space measurement concepts; field campaigns; and post-launch calibration/validation of carbon cycle space instruments, are described in the science discussions in this document.

The scientists estimated the design and development of new aircraft instruments including: ground integration and test, management, data handling/processing equipment, and interface support fixtures development. System integration and test flight costs include any special thermal/vacuum or large scale optical modifications. System integration and test flight costs were estimated at 20 or less flight hours, taking place over 2 weeks and were based on the subsidized cost per flight hour. Subsidized costs per flight hour were obtained from aircraft project offices and past mission's actual costs. Flight crew, and science team, man-hours were calculated using the principal investigator's man-hour estimates and the standard in-house cost per man-hour. Travel was estimated using standard in-house cost, and past mission spreadsheets. Costs to develop ground processing for science operations were estimated by the principal investigator. The rest of the costs are included in center, science, and spacecraft project data operations. Contingency was added to the total ensuring adequate resources.

All space and aircraft mission elements of cost as well as cost profiles are included in a separate document. These costs are presented in current year dollars (2001) instead of real year dollars because of programmatic uncertainty about the order of the missions and their actual launch dates at this early stage.

3.6 Critical Dependencies

The science and technology development program outlined in the previous sections make a number of assumptions regarding the continuation of existing and planned NASA programs and assets made available through collaborations with other federal agencies. Some of these dependencies are outlined below.

NASA Programs

1) It is expected that the Aqua, Aura, VCL, Landsat, Global Precipitation Mission (GPM), and NPOESS Preparatory Program (NPP) missions will be successfully launched. It is also assumed that (a) the key carbon observations from these missions will validated by the instrument teams with some GCCP augmentations in some cases, e.g., AIRES, (b) the data systems will be adequate to produce these products in a timely manner, and (c) archive and distribution centers such as the GSFC DAAC will be able to distribute the data at no additional expense to the GCCP.
2) The DAO will provide essential expertise and infrastructure which would be expanded to accommodate atmospheric CO_2 assimilation, transport model development, and PBL model improvement.

3) The NSIPP program will provide essential expertise and infrastructure which would be expanded for land and ocean biogeochemical data assimilation, and coupled physical-biogeochemistry model integration.
4) The SIMBIOS program will handle the intercalibration between U.S. ocean color missions (e.g., SeaWiFS, MODIS, VIIRS, Ocean Carbon) and international missions (e.g., OCTS, GLI, MERIS, POLDER) and would assist in the validation of carbon products (e.g., primary production, export production, DOC, POC) and the merger of these data sets.
5) Certain hydrological cycle observations are key to the carbon cycle, including soil moisture, soil freeze-thaw state, and ocean salinity. It is assumed that these will be provided through a hydrologic cycle initiative.
6) The AERONET array of sunphotometers is necessary for the validation of atmospheric corrections over land and oceans and will provide sites for additional CO_2 and other relevant atmospheric observations.
7) Certain NASA aircraft, e.g., the P-3, will be needed for the NACP field campaigns and it is assumed that the aircraft will be available with core flight time support.

Other U.S. Agencies
1) The NOAA CO_2 flask sampling network is essential for the NACP and for the validation of remote measurements (ground-based, aircraft, and satellite) of CO_2. It is assumed that the program will continue.
2) Shiptime will be provided during joint NASA field experiments with NOAA and NSF.

4.0 DELIVERABLES

The above investments in new global observations and related satellite data analysis will yield solid, quantitative information on the global distribution, strength, and variability of carbon sources and a sink; and the processes that regulate the fluxes and transformations between the land, ocean, and atmosphere. Error budgets in the global carbon balance will be significantly reduced, and policy-makers will have a better understanding of where the global hot spots of carbon uptake and release are. When assimilated into integrated Earth climate system models, these observations also will yield useful predictions of future atmospheric CO_2 and CH_4 concentrations, and climate change. Projections of future climate change and the scenarios used to inform assessments will be significantly improved.

A number of information and data products are anticipated as a result of the GCCP that will be of use for decision and policy making as well as for resource management. The precise timing of some of these deliverables, particularly those requiring new space-borne sensors, will depend on the technical progress made during the development phases and the measurement approach and technologies chosen for deployment. This is discussed in detail above. The timing of the achievements listed below is based roughly on the notional mission set shown in Figure 17 above.

1) Significant results and progress in the observational component of the GCCP can be achieved within the first five years by accelerating NASA's participation in the NACP, and by the development of high spatial resolution global land cover products employing Landsat to map areas of vegetation disturbance and document their rate of recovery. By resolving concern about technological readiness and then accelerating the deployment of vegetation canopy lidar technology, we also could obtain vegetation height and structural information to

produce the first, globally consistent estimate of terrestrial above-ground biomass. These and other anticipated deliverables from the GCCP are:

2) The NACP to be conducted in 2004-2006 in cooperation with other U.S. agencies will quantify the North American region's carbon sources and sinks, describe the processes controlling changes in them, and document North America's contribution to the northern hemisphere carbon sink. This will lead to better understanding of the underlying mechanisms of carbon storage and release and the roles of particular sectors and sub-regions. NASA will also be able to take advantage of the field program to establish and calibrate the field infrastructure that will be needed to validate future space-based observations of aerosols, CO_2, ocean carbon, and terrestrial biomass.
3) By 2006, an in situ network of vertical CO_2 profilers optimized for long term operation and support of future satellite validation activities will be in place.
4) By 2006, the first full report on the state of the U.S. carbon cycle, including terrestrial ecosystems, adjacent oceans, and the overlying atmosphere, will be produced jointly with other U.S. agencies, the science community, and other stakeholders.
5) By 2004-2005, an analysis of land cover change in North America for the ten-year period from 1990-2000 will be completed. By the end of 2006, land cover change in North America extended to include the period 2001-2005.
6) By late 2005, the first quantitative measurements of vegetation height and vertical structure from a space-based lidar (VCL), and local-area biomass estimates will be generated. By 2007, the first internally consistent estimates of global above-ground biomass for the Earth's forests based on a robust sampling strategy using this space-based lidar will be available. In addition, the new capability will allow us to demonstrate and evaluate the ability of this technology to measure biomass change over time for a few selected sites and short periods of time.

In the second 5-year phase of the GCCP, we will deliver observational capabilities to provide high spatial resolution atmospheric CO_2 data sets that will reduce regional uncertainties in source and sink strengths from the current 100% uncertainty to around 25% and will allow us to follow the seasonal and interannual variation in these sources and sinks and correlate them with climate-related phenomena such as ENSO. In late 2008, we will accurately locate and quantify land and ocean surface and sinks of CO_2 with regional resolution (e.g., for regions about the size of Texas) using improved inverse models and new global satellite observations of atmospheric CO_2 concentrations. We will deliver an enhanced ocean carbon data set that will permit us to significantly improve our characterization of the export of carbon to the deep sea. Carbon export to the deep sea occurs as particle sinking (the "biological pump") and subsidence of cold CO_2-bearing water (the "solubility pump"). Additional carbon fluxes to the ocean are organic matter and dissolved carbon in terrestrial runoff. Schemes for estimating these fluxes will be developed using a combination of in situ and satellite observations and models. In phase two, we will also launch advanced terrestrial biomass observational capabilities that will yield comprehensive estimates of biomass and biomass change for all terrestrial biomes, resolved at sub-regional scale, and will enable quantitative assessment of vegetation disturbance and recovery rates.

Throughout the GCCP, we can engage in focused activities that improve our analysis tools and data sets. Tools will be developed to utilize new space observations and process models. Tools for scaling regional-level understanding to the global level will also be

developed. Only at the global scale can we fully understand the transport mechanisms and rates between the land and ocean, and the impact of land-use and climate change on the global carbon cycle. These new scientific analysis tools will lead to decision support tools that decision makers can use to explore impacts of energy policies, land use policies, and climate change policies on management options. Resource managers will have more efficient and reliable methods for inventorying forests, rangelands, and croplands and assessing the impact of various management practices on crop yields, timber volume, and soil fertility.

5.0 PROGRAM COORDINATION AND STRUCTURE

The organization, scheduling, and execution of the observational component of the GCCP will require considerable planning and a clear decision-making strategy. The GCCP is highly interdisciplinary involving terrestrial, marine, and atmospheric components that must be well-coordinated and results that must be synthesized into integrated understanding of climate change. It will also require a close collaboration between the observation and modeling communities so that deficiencies in the models are adequately addressed in the field study designs and ambiguities or deficiencies in the observations are clarified by the model studies. The early phases of the observation program must address science issues and provide deliverables useful to policymakers while establishing the infrastructure to support important, new, global satellite capabilities to enable a whole new era of decision making in the longer term.

Management responsibility for planning and overseeing the GCCP ultimately resides with Code Y at NASA Headquarters which is also responsible for assuring the coordination of this program with other US and international agencies in support of the President's Climate Change Research Initiative and the broader USGCRP. As the NASA lead center for Earth Science, GSFC will assist in the GCCP implementation by assuming functions shown in Figure 21. Other NASA centers will undertake key projects in support of the GCCP, and principal investigators from a variety of academic, government, and industrial organizations will conduct key research and technology development as selected through a variety of NASA solicitations. GSFC's Earth Science Directorate will host a carbon science organization to conduct coordination and science/technology enabling activities.

Figure 21 identifies several organizations and activities that will play roles in the GCCP necessitating a program office to serve as an information exchange and coordination hub. Specific program coordination and enabling functions that a project office will need to fulfill include the following:

1) **Science team support** and coordination including grant management, and support for topical workshops, annual science team meeting, and team communications, e.g., routine distribution of progress reports and activity schedules.
2) **Resource management** (funding, instrument pools, etc.) and accounting for the science team and core science activities (described below). Instrument pools allow the project to maintain equipment and loan instruments to science team members during field deployments which avoids the need for every investigator doing field work to own instruments that are not used routinely. Programs such as SIMBIOS have managed instrument pools (submersible radiometers, sun photometers, micropulse lidars) successfully.
3) **Mission formulation** oversight would ensure that the GCCP has insight and wherever possible an involvement in the carbon mission design and engineering. The project office would maintain close communications with missions selected under ongoing programs such

as New Millinium and ESSP and would help draft solicitations for carbon-related observations.

4) **Technology development** oversight is necessary to stay up to date on the status of key technologies, e.g., lidars, and to work with NASA technology development programs, e.g., SBIR and ATIP, to help ensure critical technologies are adequately represented and systematically progress to the required TRLs.
5) **Outreach and documentation**, e.g., annual program reports and routine status presentations, are necessary to ensure the accomplishments of the GCCP are brought to the attention of NASA management, the science community, the new media, and the public at large. This can be accomplished in a number of ways including organizing special sessions at key national and international conferences, e.g. the American Geophysical Union and American Meteorological Society meetings, close communication with NASA public affairs, and maintenance of a carbon cycle website.
6) **Interagency coordination** is essential for the NACP, the Southern Ocean study, and other related activities to be successful executed. High level coordination will be handled by the IWG, but more detailed coordination will need to be worked at the project level.

It is envisioned that a number of core science activities will be undertaken, some by existing NASA groups or programs that are already undertaking related research so that scales of economy can be realized to reduce cost. The project office would provide funding to these groups, track their progress, and expedite interactions between the groups. These include the following:

1) **Data synthesis and reanalysis** which entails the collection, collation, and integration of a variety of carbon-related data sets (in situ, satellite, model) into data products required by the science team for addressing the GCCP goals and objectives. In some cases, this may involve the reanalysis of historical data sets such as Landsat and ocean color data sets. For some instances, existing projects can be easily augmented to undertake these reprocessings, e.g., the SeaWiFS Project for ocean color data reanalyses.
2) **Global data assimilation** involves the development of assimilation methods, improved models including coupled physical-biogeochemical models (under the guidance of the science team), and the generation of model products for the science team. The DAO and NSIPP are ongoing programs that are well positioned for such tasks and NSIPP has an existing science team that could contribute to carbon-related assimilation model development and analyses.
3) **Data management** involves the archival and distribution of carbon data sets, particularly large data sets from satellites and models. In the case of satellite data, the GSFC DAAC would be the most likely candidate. In the case of ocean bio-optical data, the SIMBIOS project, in collaboration with the SeaWiFS Project, is already maintaining a large database that is easily accessed by the ocean color community.
4) **Field program coordination** will be required as the GCCP and the Southern Ocean study will undertake a wide variety of field studies involving many different groups and logistical challenges, e.g., ship and aircraft scheduling. Based on previous studies such as the Boreal Ecosystem-Atmosphere Study (BOREAS), a dedicated group should be supported to insure that the infrastructure and logistics are properly handled. The project office could be staffed to assume these responsibilities, or this function could be competed through an NRA for each major field campaign.

5) **Global coupled model computing support** is essential as these models will be some of the most sophisticated, complex, and compute intensive ever developed and will require access to a supercomputing facility (Code 930 at GSFC).

6.0 APPENDICES

APPENDIX 1. USGRCP CARBON RESEARCH GOALS

The USGRCP carbon research goals, as identified at the time of the first workshop, are listed below. The GCCP working group adopted these at the first workshop as primary objectives, considering them to be totally consistent with the ESE strategy, and designed future GCCP activities to address them. In all cases, the GCCP can make a contribution, although some subtopics are beyond the scope of the GCCP, e.g., 5a. Figure 20 illustrates how the GCCP activities map onto these goals. These goals have been refined since the workshops, but not substantially.

1) Quantify North American carbon sources and sinks and the processes controlling their dynamics.

a. Strengthen and fill gaps in regional and continental-scale forest inventory, soil carbon, productivity, atmospheric carbon, and CO_2 flux databases.
b. Identify the processes controlling carbon sources and sinks through manipulative experiments, studies of disturbance, and integration of decision sciences and risk management studies.
c. Conduct a comprehensive field campaign for North America in concert with atmospheric inversion and ecosystem modeling to close the North American carbon budget and reduce errors through rigorous model-data comparisons and scaling protocols.

2) Quantify the ocean carbon sink and the processes controlling its dynamics.

a. Quantify global air-sea fluxes of CO_2 and the spatial distribution of carbon in the ocean on seasonal to interannual time scales using both remote and direct measurements.
b. Understand the role of micro- and macronutrients, species functional groups, and modes of climate variability in controlling carbon transfers and storage in the ocean.
c. Improve model representations of ocean carbon dynamics and physical circulation.

3) Report the "state of the global carbon cycle" annually.

a. Establish and ensure the continuity of a global carbon observing system in cooperation with international partners.
b. Develop an analysis framework to incorporate data and process constraints from multiple sources.
c. Evaluate the relative roles of processes in the ocean and on the land in determining the interannual growth rate in atmospheric CO_2.
d. Provide integrated information on carbon stocks, fluxes, terrestrial and marine productivity, and the natural and human processes controlling CO_2 and CH_4 growth rates.
e. Develop new remote sensing technologies to quantify global carbon sources and sinks.
f. Assess the needs of stakeholders and decision-making processes and ensure that carbon cycle information is useful.

3) Evaluate the impact of land use change and land and marine resource management practices on carbon sources and sinks.

a. Analyze the effects of historical and contemporary land use across environmental gradients.
b. Quantify carbon storage and release due to land management practices, including those designed to enhance carbon sequestration in biomass and/or soils.
c. Evaluate the fate of carbon in ecosystems that are subject to disturbances such as fire, conversion to agricultural uses, extractive harvest, in situ degradation, urbanization, webland creation or drainage, and exogenous inputs of sediments, nutrients, and pollutants.
d. Link ecosystem, resource management and human dimensions models to evaluate a wide range of forest, agricultural, and coastal ocean policy scenarios, and consumer and producer welfare.

5) Forecast future atmospheric CO_2 concentrations and changes in terrestrial and marine carbon sinks.

a. Develop new and integrative approaches for conducting social science research to understand how humans affect the carbon cycle.
b. Develop new approaches to accommodate differences in scale, complexity, and modeling structures to link physical, biogeochemical, and human system models focused on predicting carbon cycle dynamics.
c. Project future atmospheric CO_2 and CH_4 levels and changes in carbon reservoirs using dynamic Earth system models. These models should incorporate an improved understanding of physical processes, climate, nutrients, the structure and function of ecosystems, fire, changes in permafrost, other environmental changes, and effects of human activities, such as energy production, use of alternative energy sources, and land and marine resource use.

6) Provide the scientific underpinning, and evaluations from specific test cases, for management of carbon in the environment.

a. Perform manipulative experiments to understand the effects of enhanced nutrient availability on carbon uptake in the ocean and of elevated CO_2 on terrestrial plant physiology and carbon allocation.
b. Conduct field and modeling studies to evaluate the effectiveness of deliberate management strategies to manipulate carbon in the ocean, on land, and in the atmosphere and to assess their impacts on natural and human systems, taking into account multiple interacting influences.
c. Provide scientific criteria to evaluate the vulnerability and sustainability of carbon sequestration and/or emissions reduction approaches and of the incentive systems to promote their adoption.
d. Develop monitoring techniques and strategies to measure the efficacy of carbon management activities.

As discussed in the main text, there are a number of historical, on-orbit, approved, and proposed missions that can contribute to the USGRCP goals, both near term and long term. Table 1 provides a brief compilation of the instruments as they apply to the various processes associated with major land-ocean-atmosphere carbon flux categories, i.e., 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 North American Carbon Program (NACP, goal #1), in particular, would offer opportunities for these purposes, but additional independent NASA-sponsored experiments will probably be required in order to obtain data sets of sufficient diversity and completeness. Note that Table 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 to be the most critical to efforts such as 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 1 entries include contributions from the IIP, the NMP, and the ESSP. The IIP produces prototype instruments which may be deployed on aircraft. New Millenium missions, e.g., 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 (1-2 years), e.g., 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 field campaigns include passive and laser CO_2 airborne systems. The ESSP selections have not been announced and are subject to additional down-selections before final approval, so it is unclear at this time what the future ESSP contributions will be.

Under the GCCP, several carbon-related observations have been identified including:

1) Atmospheric CO_2 concentration;
2) Stocks and rates of change in terrestrial biomass;
3) Oceanic primary productivity and dissolved organic carbon;
4) Air-sea CO_2 fluxes.

While the existing/scheduled instruments in Table 1 can contribute to these measurement needs, few are optimized for these purposes which is why new missions are desired. Unless some of these observational needs are met under the most recent ESSP selection process, spaceborne observations of these quantities will be limited during the early phases of the NACP, but will be in place for the Southern Ocean program.

The NASA GCCP includes field studies aimed at improving model parameterizations of key carbon cycle processes with satellite data assimilation for enhancing model accuracy and earth system predictability. Wherever possible, field data collection for process model development, remote sensing algorithm development, and product validation will be integrated. This framework of observations and modeling parallels that of the NACP was designed with the NACP in mind as a first step towards developing a global capability in collaboration with other U.S. and international agencies.

APPENDIX 2. NASA ESE CAPABILITIES AND CONTRIBUTIONS TO CARBON CYCLE STUDIES

A2.1 Land Summary

The focus of NASA's remote sensing and science activities has been to better utilize satellite observations to provide information of interest to NASA's ESE discussed in section 1.4. Earth resources satellites such as Landsat and MODIS only directly observe the quantity of

electromagnetic radiation emitted or reflected from the Earth's surface. These direct measurements must be converted into biophysical and other parameters using algorithms, which in turn are used in biogeochemical and physical models that relate these parameters into useful ecological and climate information. There is an intimate relationship therefore between observations, algorithms and modeling that has been the primary focus of exploration in NASA's funded field experiments described in the sections to follow.

Satellite-based observing systems

In addressing ocean, atmosphere and land observations, NASA has developed and launched an impressive array of satellites that map and measure a wide range of atmospheric, land and ocean phenomena. The sensors operate over a broad range of application-specific frequencies (ultraviolet, visible, near-, mid-, and thermal infrared, and microwave), spatial resolutions (15m to tens of kilometers), and temporal frequencies (twice hourly to bi-weekly). Some sensors measure reflected solar radiation at these frequencies (passive sensors) while others (active sensors) generate and measure back-scattered radiation. Multiple instruments have been flown on the same platform and on separate simultaneous platforms. NASA has encouraged and enabled multidisciplinary approaches to the study of Earth system science with a consistent observational framework.

The heritage of NASA observational platforms spans nearly four decades, beginning with the Television Infrared Observation Satellite (TIROS) series of experimental meteorological satellites in the early 1960's, ultimately leading to the NOAA series of operational polar orbiting satellites beginning in the early '70s, and continuing today with the Terra observing system. Landsat was another major initiative beginning in 1972. Six Landsats have been successfully launched including Landsat 7 currently in orbit. NASA's Landsat series has provided nearly 30 years of high-spatial resolution mapping of the Earth's surface and its changes in land cover due to deforestation, climate variability, etc. A new series of satellites designed to monitor ocean color was initiated with SeaWiFs, launched in 1997 as a successor to the proof-of-concept coastal zone color scanner (CZCS), and is capable of measuring land vegetation. NASA currently has a number of future missions on the drawing board to continue the monitoring of the Earth's systems, including the newest addition, active optical sensors (lasers). These new sensors and platforms are carefully selected to augment NASA's space assets critical to a complete understanding of the Earth as a system as well as the global carbon cycle.

Advanced Very High Resolution Radiometer (AVHRR)

The AVHRR was developed by NASA and has been flown on the NOAA satellites since the early 1980s. NASA has supported research, data production, product development and distribution of vegetation products at spatial resolutions as fine as 1 km. Visible and near infrared bands, while designed for meteorological and ocean sea surface temperature (SST) observations, were adapted to land vegetation observations to produce a nearly two decade time series of global land vegetation measurements. These measurements have been used to link climate interannual variability and trends to vegetation disturbance, vegetation type and changes in vegetation. AVHRR also has been used to study fire (hot spot detection, area burned) and extract BRDF related information. Data products include the Pathfinder Normalized Difference Vegetation Index (NDVI) data set, a global monthly composited series extending from 1982, the International Satellite Land Surface Climatology Project (ISLSCP) I data set, and a global 1-degree two year data set (1987, 1988) with carbon model parameters derived from NDVI (land

cover type, and vegetation biophysical parameters). The ISLSCP I data set has been used extensively to compare various bottom-up model predictions at global scales. ISLSCP II will extend the 1987-1988 ISLSCP I data set another 10 years, 1986-1995, and add significant new data sets related to surface-atmosphere carbon flux modeling.

Landsat

Landsat 1, launched in 1972, initiated a series of global earth resources satellite images with high spatial resolution (15-75m) that continue today, producing nearly three decades of land surface measurements. Landsat provides observations of disturbance (deforestation, burn area) and land use change, biophysical parameters, and vegetation classification, all at finer scales but less frequently than AVHRR products. A Landsat pathfinder data set funded by NASA currently focuses on tropical deforestation. The pathfinder data set consists of scenes from the mid-'70s, mid-'80s and mid-'90s and deforestation and secondary regrowth estimates over this time period. In the long term, Landsat data will be collected to provide a global archive at least 4 times per year.

SeaWiFS

SeaWiFs was designed primarily for measuring surface ocean chlorophyll concentration, but is also capable of measuring land vegetation. While the operational global area coverage (GAC) is subsampled on the spacecraft to every fourth pixel and line, a 1-km data set from High Resolution Picture Transmission (HRPT) stations cover most of the northern hemisphere land masses. The 4-km data is routinely collected globally and has been used to estimate monthly NDVI and terrestrial productivity.

The Scanning Multi-channel Microwave Radiometer (SMMR) and the Special Sensor Microwave/Imager (SSM/I)

To date, microwave technology has been the only viable option for measuring soil moisture under a variety of topographic and vegetation cover. The major factor inhibiting wide spread use of remotely sensed soil moisture data in hydrology is the lack of data sets and optimal satellite systems. For the most part, passive microwave data have been collected only from short duration aircraft campaigns, or from the satellite-borne SMMR and SSM/I instruments, which are not optimum for observing soil moisture through most vegetation. Even with this restriction, however, global soil moisture estimates have been made using these satellites. Theory shows that data from the SMMR passive microwave system is more optimum for soil moisture estimates than the SSM/I data because SMMR wavelengths are more sensitive to soil moisture; however, its period of record is limited (1978-1987). In both cases the footprint is rather large, varying from about 25 km for the SSM/I to about 150 km for the C-band SMMR. The 150 km footprint, however, limits the utility of the soil moisture data for carbon cycling modeling. Investigations of more advanced satellite systems are underway, such as passive microwave systems using aperture synthesis to obtain higher spatial resolution.

Synthetic Aperture Radar (SAR)

Beginning with the SEASAT in 1978, and the shuttle missions with Shuttle Imaging Radar (SIR)-A, SIR-B and and SIR-C in 1981, 1984 and 1994, respectively, NASA has launched a number of active microwave (radar) space missions for biomass estimation, land cover classification, change detection (burned area) flooding and inundation and soil moisture. NASA

has also developed and flown a number of aircraft active microwave instruments. Microwaves have at least two advantages over optical frequencies: (1) cloud penetration and (2) increasing vegetation penetration to soil at increasing wavelengths. Thus, microwaves provide an all weather imaging capability over a wider range of vegetation types, particularly important in regions with high amounts of cloud cover such as the tropics and the high-latitude boreal ecosystem. Currently, no NASA land radar missions are on orbit. As opposed to the dominance of the US in passive optical space missions, active microwave space missions have been dominated by other nations such as Europe (European Remote-sensing Satellite (ERS)-1, ERS-2), Japan (Japananese Earth Remote-sensing Satellite (JER)-1), Canada (Radarsat) and Russia (Advanced Land Observation Satellite (ALOS)).

Only limited regional vegetation data products have resulted from NASA space and aircraft microwave missions. SEASAT lasted only 3 months, and the shuttle missions just a few days, limiting coverage to non-contiguous swaths; however, a global rainforest mapping project and global boreal forest mapping project involving aircraft SAR scenes in 1995 and 1996 is underway. Also planned is a NASA data buy of radar and elevation data from an airborne Interferometric Synthetic Aperture Radar for Elevation (IFSARE) system. The data will be useful for a wide range of applications involving land use, land cover, and terrain modeling.

SAR systems offer perhaps the best opportunity to measure soil moisture routinely over the next few years. Currently, the ERS-1 C-band and JERS-1 L-band SARs are operating as is the Canadian Radarsat (also C-band). Although it is believed that an L-band system would be optimum for soil moisture, the preliminary results from the ERS-1 demonstrate its capability as a soil moisture instrument. Change detection techniques have been used to detect changes in soil moisture in Alaska. However, radar data become ambiguous in areas where inundation by surface water is frequent. One main drawback to the existing SAR systems is that there are no existing algorithms for the routine determination of soil moisture from single frequency,single polarization radars. A second limitation comes from their long period between repeat passes, usually 35 to 46 days, although the RADARSAT has 3-day capability for much of the globe in a "scansar" (wide swath, 500 km) mode.

Moderate-Resolution Imaging Spectroradiometer (MODIS)

MODIS scans every point on the globe over a 2,330-km-wide viewing swath every 1-2 days in 36 discrete spectral bands. In comparison to AVHRR, MODIS' improved sensor radiometric characterization, calibration, spectral resolution and spatial resolution should result in greatly improved estimates of carbon-related parameters such as leaf area index (LAI), fraction of photosynthetically available radiation (fPAR), vegetation classification, net primary productivity (NPP), vegetation change detection, fires, canopy water content, chlorophyll, and SST. MODIS also provides ancillary information such as the percent of the planet's surface that is covered by clouds. MODIS is ideal for monitoring large-scale changes in the biosphere that will yield new insights into the workings of the global carbon cycle. While no current satellite sensor can measure carbon dioxide concentrations in the atmosphere, MODIS can measure the photosynthetic capacity of ocean and land plants, when combined with solar insolation and other climate variables, and yield better estimates of how carbon dioxide is being absorbed and used by plants. MODIS also maps the areal extent of snow and ice. Some MODIS bands are particularly sensitive to fires; they can distinguish flaming from smoldering burns and provide better estimates of the amounts of aerosols and gases fires release into the atmosphere.

Multi-angle Imaging Spectroradiometer (MISR)

To fully understand Earth's climate, and to determine how it may be changing, we need to know the amount of sunlight that is scattered in different directions under natural conditions. MISR is a new type of instrument designed to address this need. It will view the Earth with cameras pointed at nine different angles. One camera points toward nadir, and the others provide forward and aft view angles, at the Earth's surface, of 26.1°, 45.6°, 60°, and 70.5°. As the instrument flies overhead, each region of the Earth's surface is successively imaged by all nine cameras in each of four wavelengths (blue, green, red, and near-infrared). In addition to improving our understanding of the fate of sunlight in the environment, MISR data can distinguish different types of clouds, aerosol particles, and surfaces. Specifically, MISR will monitor the monthly, seasonal, and long-term trends in:

(a) the amount and type of atmospheric aerosol particles, including those formed by natural sources and by human activities; and
(b) the amount, types, and heights of clouds; the distribution of land surface cover, including vegetation canopy structure.

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)

ASTER obtains high-resolution (15 to 90 square meters per pixel) images of the Earth in 14 different wavelengths, ranging from visible to thermal infrared light. ASTER data can be used to create detailed maps of land surface temperature, emissivity, reflectance, and elevation. ASTER is the only high spatial resolution instrument on the Terra platform. ASTER's ability to serve as a high-resolution sensor supporting other Terra lower resolution instruments is particularly important for change detection, and land surface studies. Unlike the other instruments aboard Terra, ASTER will not collect data continuously; rather, it will collect an average of 8 minutes of data per orbit. All three ASTER telescopes, visible and near-infrared (VNIR), short wave infrared (SWIR), and thermal infrared (TIR), are pointable in the crosstrack direction. Given its high resolution and its ability to change viewing angles, ASTER will produce stereoscopic images for detailed terrain height models.

Field programs

Over the past few decades NASA has led or strongly supported numerous meteorological, ecological, biogeochemical process and hydrological field studies at scales ranging from plot levels to continental scales. Field experiments have been pivotal in the development of global change models, development and validation of remote sensing algorithms, and improving sensor calibration and atmospheric correction techniques. The locations of the various field experiments were selected to represent the Earth's major biomes, sequenced so as to encounter a graduated series of increasingly more difficult challenges. The experiments were designed to coordinate process studies with remote sensing investigations using satellite, airborne, and surface-based instruments. In the initial stages of experiment design, remote sensing images provided local and regional land cover maps to select study sites within biomes and to pinpoint measurement locations representing the important biome vegetation communities. The remote sensing studies were essential to scaling up process models from leaf and plot levels, and from plots to regional and global scales. Large-scale validation techniques were incorporated into the field experiments to test scale-integration methods directly. These techniques included airborne flux and profile measurements, meteorological observations, and modeling. NASA's major field programs have focused primarily on grassland biomes in the US

(the First ISLSCP Field Experiment (FIFE)), the cold northern or boreal forests in Canada (BOREAS) and the tropical forests of the Amazon Basin (the Largescale Biosphere-atmosphere experiment in Amazonia (LBA)). Table A1.1 shows a list of some of the land-surface related field campaigns during the last 20 years.

Table A2.1. NASA supported field experiments.

Name	Location	Period	References
Hydrological and Atmospheric Pilot Experiment - Modelisation du Bilan Hydrique (HAPEX-MOBILHY)	Southern France	1985-1987	Andre et al. (1989)
First ISLSCP Field Experiment (FIFE)	Central Kansas, USA	1987-1989	Sellers and Hall (1992), Hall and Sellers (1995)
Hydrological and Atmospheric Pilot Experiment in the Sahel (HAPEX Sahel)	Western Niger	1991-1993	Goutorbe et al., (1994)
Boreal Ecosystem-Atmosphere Study (BOREAS)	central Canada	1993-1996	Sellers et al. (1997), Hall (1999)
Southern Great Plains (SGP)	Oklahoma and Kansas, USA	1997, 1999, 2001	http://hydrolab.arsusda.gov/sgp97/ http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/SGP99/
Large Scale Biosphere-atmosphere experiment in Amazonia (LBA)	Brazil	1996-2001	http://lbaecology.gsfc.nasa.gov/lbaeco/About_the_Project/introduction.htm
Safari 2000	Zambia, Africa	2000	http://www.safari2000.org

NASA has also funded the establishment and operation of numerous sites for evaluating land data products (Figure A2.1). The primary validation techniques include collection of and comparison with field and aircraft data, and comparison with data products from other satellites. To adequately cover the broad range of surface-atmosphere systems that will be encountered around the world, a global array of test sites is used with multiple validation methods applicable to different temporal and spatial scales.

Within the field experiments a major focus was development of remote sensing algorithms of vegetation type and biophysical properties at regional and global scales. These parameters were important in modeling the photosynthetic uptake of carbon and the physiologically coupled release of water and its effects on the surface energy budget. Algorithms were also developed and tested for measuring incident short and long wave radiation and PAR, the fraction of these absorbed by the vegetation, and the subsequent release back to the atmosphere in the form of reflected short wave radiation, emitted long-wave radiation, latent and sensible heat.

First ISLSCP Field Experiment (FIFE)

FIFE was an international, land-surface-atmosphere experiment centered on a 15x15 km test site near Manhattan, Kansas. The objectives of FIFE were to better understand the role of biology in controlling the interactions between the atmosphere and vegetated land surface and to investigate the use of satellite observations for inferring climatologically significant land surface parameters. FIFE occurred in two experimental phases, 1987 and 1989, followed by several years of funding for science analysis. FIFE focused on improving surface representations for general circulation and climate models to include the effects of land vegetation on surface energy and radiation balance and the development and validation of remote sensing algorithms to infer surface parameters critical for quantifying the surface energy and radiation parameters. There was a smaller focus on the relation of land-atmosphere carbon flux, investigating the connection between photosynthetic uptake of carbon dioxide and water. In 1986, 29 multidisciplinary investigator teams were selected to participate in FIFE through a peer review process. FIFE resulted in (1) improved understanding of the exchanges between the land surface and the atmosphere at the local scale (1-100m); (2) application of remote sensing science at the local scale; (3) use of remote sensing and models to describe surface-atmosphere exchanges at intermediate scales (100m-15km); and (4) improvement of measurement capabilities and experimental techniques.

A major focus of FIFE was the development of remote sensing algorithms to produce seasonal, annual and decadal maps of vegetation type and biophysical properties at regional and global scales important in modeling the photosynthetic uptake of carbon and its effects on the surface energy budget. At the outset of FIFE, NDVI and its derivatives were widely used for continental to global monitoring, but with limited understanding and validation. Global images of composited AVHRR NDVI corresponded well with known surface patterns of vegetation type and their variation with climate, but the quantitative use of vegetation indices to monitor surface energy, water and carbon exchange had not been developed. What were the vegetation indices measuring? By combining careful analyses with ground and aircraft-based measures of surface reflectance, vegetation biophysical properties, and atmospheric and illumination effects for a number of different vegetation types, under a wide range of seasonal and meteorological conditions, field experiments quantified the behavior and utility of a variety of vegetation indices and stimulated their wide use.

Boreal Ecosystem-Atmosphere Study (BOREAS)

BOREAS was an interdisciplinary, multiscale field experiment to study the role of the boreal ecosystem in global change. Eighty-five science teams, including atmospheric physicists, micrometeorologists, ecologists, hydrologists, biogeochemists and remote sensing specialists were involved. The objectives of BOREAS relate to two spatial scales that had to be reconciled within the experiment design: the local scale, a few centimeters to a kilometer, and the regional scale from a few kilometers to the 10^6 km^2 BOREAS study region in central Canada. The primary focus of local scale experiments was to improve and characterize the performance of the process models that describe the exchanges of radiative energy, water, heat, carbon, and trace constituents between the boreal forest and the atmosphere. The regional-scale experiments were concerned with applying and validating the process models over large spatial scales using remote sensing. In BOREAS, as in previous field experiments such as FIFE, and the Hydrological Atmospheric Pilot Experiment, HAPEX-Sahel, the science team adopted a nested multiscale measurement strategy to integrate observations and process models over the scale range. During

1993 through 1996, the BOREAS science team consisted of over 300 scientists. BOREAS was originally planned to last three years, with field campaigns in the first year and disciplinary data analysis occurring in the second and third years. However, analyses performed in the second year of BOREAS showed that there were a number of gaps in the first year's data; thus a third year of data collection was proposed and funded, along with an additional fourth year to analyze the data. During the first four years of BOREAS, scientists focused on acquiring, quality assuring and analyzing their own data; process model work focused mainly on analyzing tower site data for model development and validation.

In BOREAS, process and modeling studies were coordinated with remote sensing investigations using satellite, airborne, and surface-based instruments that focused on methods for quantifying critical state variables. A range of observational techniques and platforms were used to characterize surface component optical properties from the leaf to the canopy and stand level to the study area and regional level. Both optical and microwave scattering properties were measured. Local-scale measurements were used to develop physically-based remote sensing algorithms to produce validated multi-scale land cover parameter maps and importantly, the first maps of the freeze/thaw status of canopies and soils. These multiscale, multiyear parameters were used to force the surface-atmosphere carbon, water and energy flux models. Models were then validated through model intercomparison and sensitivity studies and through direct comparison of tower-measured fluxes. The parameter images, generated at a variety of spatial resolutions and geographic scales, also permitted studies of algorithm and model invariance with scale.

BOREAS catalyzed several advances in remote sensing algorithm development that permitted boreal vegetation to be monitored by type and state, and to track changes that may be due to fire, direct human activity, or climate change. Algorithm developments during FIFE and BOREAS have led to the production of AVHRR-derived global vegetation maps spanning 1981 to 2000, time-series fields of land cover, biophysical parameters, phenology and snow cover. All these can be compared with the physical climate record and to seasonal and interannual variations in atmospheric CO_2 concentration. AVHRR data will also be used to monitor changes in the fire disturbance regime over the same period of record. The radiometric quality of the AVHRR data series will have to be enhanced to meet these tasks; this requires the development of techniques for improving long-term calibration and atmospheric correction of the data. The MODIS, MISR and other sensors should soon provide significant additional capability for monitoring land. Finally, the use of radar satellites such as ERS-1 and JERS-1 have been used to monitor the interannual variability in the freeze-thaw boundary in the boreal ecosystem, shown to be a key factor in the interannual variability of the carbon flux. To take advantage of the different attributes of optical and radar sensors, further remote sensing research and development is required; in particular, data fusion algorithms, that combine optical and microwave sensors as well as other data such as topographic data, could be developed to provide richer information about the biome.

The results of the BOREAS investigations appear in an 85-paper volume of the Journal of Geophysical Research-Atmospheres BOREAS special issue [Sellers et al., 1997], an eleven-paper volume of the BOREAS special issue of Tree Physiology [Margolis and Ryan, 1997], and a nine-paper volume of the Canadian Journal of Remote Sensing [O'Neill and Ranson, 1997]. In addition, over 345 other journal articles are listed on the BOREAS information system (http://boreas. gsfc.nasa.gov/BOREAS/ Papers.html). As an example of the kinds of science that

come from the NASA field programs, a brief summary of the BOREAS science findings is given below.

BOREAS Science Summary

The "top-down" modeling approach discussed in section 2.0 above, suggests that during the 1980's the northern continents acted as a large sink for atmospheric carbon, (1 to 2 gigaton (Gt) C yr^{-1}), or about 15 to 30% of the anthropogenic CO_2 flux from fossil fuel burning. The exact biophysical mechanisms responsible for this sink are unclear, although the hypothesized lengthening of the growing season could be a factor (Keeling et al., 1996; Myneni et al., 1997). The boreal ecosystem is vast, covering an area of some 20 million km^2 (Sellers et al., 1997). Simple arithmetic implies then, that on average only 50 to 80 g C m^{-2} yr^{-1} need be sequestered to account for a 1 GtC yr^{-1} global sink. Results from BOREAS (Hall, 1999) show that this number is well within the range of annual carbon uptake values estimated from eddy correlation data acquired at the BOREAS tower sites. But to extrapolate these measurements into the future over the entire boreal zone, even from several years of data, necessitates a deeper understanding of the climatological, physiological, and other processes controlling carbon uptake and respiration. From the outset, an important objective of BOREAS was to acquire the data needed to improve terrestrial carbon models for the boreal region. In particular, data were needed to improve our understanding of the dependence of carbon fluxes on physical climate variations and to develop methods for extracting useful parameters from satellite data. Any improved understanding of the carbon cycle had to take into account the physical climate system, strongly coupled to the global carbon cycle. For example, temperature and precipitation anomalies have been compared with seasonal variations in atmospheric CO_2 concentration and isotopic analyses to show that warm years over the northern continents are associated with a net terrestrial carbon sink, while cold and/or dry years are associated with a net source of terrestrial carbon (Keeling et al., 1996; Ciais et al., 1995; Denning et al., 1995; Tans et al., 1990). Thus, BOREAS was designed to include measurements of not only the direct carbon cycle, but also the major carbon-relevant climate components.

Carbon sequestration in the boreal ecosystem amounts to the relatively small difference between gains from photosynthesis and losses due to respiration in the plants, roots and soils. For roughly the past 8000 years following the last glaciation, the boreal ecosystem has been accumulating carbon in its soils, particularly in deep layers of organic peat where soil organic matter accumulates under water-saturated conditions. Harden et al. (1992) place historical carbon accumulation rates in these peat soils in the range of 10 to 50 g C m^{-2} yr^{-1}. On shorter time scales, primary carbon storage mechanisms appear to be in above-ground standing biomass and below-ground accumulation through surface moss production, fine root turnover and litter fall. The progressive warming that occurred during the 1980s and early 1990s could have altered rates of photosynthesis, respiration and fire frequency in the region. In addition to driving changes in the ecophysiology of the biome, continued warming could eventually alter the spatial structure of the boreal ecosystem. There have been several attempts to map the future extent of the northern biomes based on the projected warming and drying regime due to a "doubled CO_2" climate. Some of these suggest that the North American boreal forest would move north and perhaps split into two halves; one in Alaska and the Canadian Northwest, and the other in the Canadian Northeast (Rizzo and Wiken, 1992). Such changes may themselves have significant feedbacks on the climate system through changes in the winter albedo and energy fluxes over the altered land surfaces.

The boreal ecosystem can be generally divided into roughly into uplands and peatlands, the uplands supporting tree growth on mineral soils with net ecosystem exchange in the range of 100 to 300 $gCm^{-2}y^{-1}$. The uplands burn once every hundred years on the average, thus can only store carbon over multi-decadal time scales. Peatlands, however, store carbon below ground with long-term (centuries to millennia) carbon accumulation rates in the range of 10 to 50 $gCm^{-2}y^{-1}$. Thus, the rate at which the global boreal ecosystem stores carbon has a secular component of about 30 $gCm^{-2}y^{-1}$ or about 0.6 petagrams (10^{15} grams) annually, with seasonal and decadal fluctuations driven by climate variation and disturbance. For example, in Canada the total area disturbed was large during 1860-1920 and 1980-1998 leading to increased uplands carbon uptake in the decades between.

Since 1970, climate change has had a significant impact on snow cover, which may have enhanced spring warming through feedbacks from the subsequent decrease in surface albedo. The boreal ecosystem has experienced a significant reduction in spring snowpack over the later half of the twentieth century and an overall decrease in the seasonal duration of snow cover. Snow cover reductions were on the order of 1.0 day yr^{-1}. However there were regional variations. The boreal forest region of North America, heavily forested by evergreen conifers, showed relatively little change in spring snow cover perhaps because the snow cover feedback is weak, due to strong shadowing by the evergreen conifers which reduces markedly the difference between snow-on and snow-off albedo. In Eurasia, where deciduous conifers are abundant, snow-on versus snow-off albedos differ significantly and most of this region experienced spring snow cover reductions.

This high-latitude ecosystem differs dramatically from temperate and tropical ones. The surface energy balance can change in just a few days as the boreal snow cover melts, the frozen peats beneath begin to thaw allowing photosynthesis and evapotranspiration. The boreal ecosystem is for the most part, a wetland ecosystem composed of nutrient-limited conifers growing on cold, moisture-saturated peats. In spite of this ecosystem's water-saturated surface, the atmospheric boundary layer is often dry and deep, more characteristic of an arid ecosystem. The deep, dry boundary layers overlying a water-saturated surface led to the apt description "the green desert".

Climate warming is most rapid at these latitudes, as much as 1.25°C per decade with much of this warming occurring in the spring and fall. Tower flux and chamber measurements of above and below ground photosynthesis and respiration have helped to elucidate the dynamics and ecophysiology of boreal carbon exchange and how climate changes might alter the source/sink relationships within this ecosystem. Tower flux measurements show that the wetlands fluctuate between being a weak source to a weak sink of carbon with source/sink strengths of about ± 50 g cm^{-2}. Tower measurements also showed that this small net ecosystem exchange was the net difference between two much larger carbon flux rates of about 1 kg of carbon uptake from net primary production and about 1 kg of carbon loss from heterotrophic respiration, primarily a result of soil decomposition. Over those years, annual net primary production was rather more stable than heterotropic respiration.

Other detailed studies showed that net ecosystem exchange in the boreal ecosystem is enhanced by early snow melt and subsequent soil thaw which initiates early photosynthetic uptake of carbon while the soil is still relatively cool and heterotropic respiration is low. For the same reason, cool summers and late falls also enhance net carbon uptake. Heterotrophic respiration is fundamentally a function of soil temperature. Thus, years with longer growing seasons and cool summer soil temperatures should, in general, be associated with increased

carbon uptake. Shorter growing seasons on the other hand, with hot summers and warmer soil temperatures should be, in general, associated with increased carbon release. If the strong high-latitude warming trend continues, leading to warmer soils and a reduction in the extent of the boreal permafrost zone, the resultant increases in soil organic matter decomposition could switch the boreal ecosystem from a long-term carbon sink to a significant carbon source.

Myneni et al. (1997) analyzed AVHRR global time series and showed that over the past decade, the growing season and photosynthetic capacity increased over large areas of Europe, northern Eurasia, Alaska and Canada. This satellite result supported the work of Keeling et al. (1996) who analyzed time-series of atmospheric CO_2 concentrations to show that warming has led to a lengthening of the approximately 150-day growing season by about six days at higher latitudes.

NASA has also funded a number of activities to improve the land surface parameterizations (LSPs) and surface parameter sets used in AGCMs . As a result, these models have improved considerably over the last decade, (Sellers et al., 1997). Climate models use many of the same formulations, submodels and parameters as numerical weather prediction (NWP) models; the latter also benefit from a continuous process of operational verification. Results of large-scale NASA field experiments were implemented within months, first into NWP models (Betts et al., 1993, 1996, 1997a, b) and later to climate models (Sellers et al., 1997). Analyses have demonstrated that until very recently, even the best NWP models consistently over-predicted the evaporation rates and specified unrealistic winter albedo fields over the boreal region with serious consequences for forecasting skill (Betts and Ball, 1997). The reasons for these errors were directly connected to misrepresentations of important biophysical processes in LSP's, for example, controls on evapotranspiration, and inaccuracies in specifying model parameters, such as the extent, type and density of forest biomes.

A2.2 Oceans Summary

Ocean color measurements

NASA has a long history of activities oriented towards physical and biological remote ocean observation systems. Historically, these have been technology driven applications, but more recently, are the result of science driven technology development. Early instruments such as the Very High Resolution Radiometer (VHRR), originally designed for meteorological applications, proved valuable for SST estimation and lead to the second generation Advanced VHRR (AVHRR) which has been in operational use by NOAA for nearly 20 years. At this time, high accurate satellite observations of SST, sea level, surface winds, chlorophyll-a, diffuse attenuation coefficient (water clarity), and other parameters are routinely generated by a variety of U.S. and international satellite programs.

The feasibility of measuring surface chlorophyll-a concentrations using an airborne radiometer was first demonstrated in the late 1960's by a group at Woods Hole Oceanographic Institute. This led to the development of a number of low and high altitude airborne ocean color systems, e.g., the U-2 Ocean Color Scanner, at different NASA centers (LaRC, ARC, GSFC, Glenn Research Center (formerly Lewis Research Center) and JPL) over the next decade. Initially, work focused on turbid coastal waters with high reflectances because it was believed that the lower reflectances of open ocean water could not be quantified in the presence of large atmospheric Rayleigh and aerosol reflectances. Both GSFC and Langley had active programs in marine optics during the 1970s which were discontinued by the early 1980s. In the 1990s, the MODIS, SeaWiFS, and SIMBIOS programs have supported expansive field measurement

programs for calibration and validation which include the Marine Optical Buoy (MOBY), calibration round-robins, field and in situ instrument development, measurement protocol definition, atmospheric and bio-optical algorithm development, and realtime in situ bio-optical data acquisition systems (both at GSFC and SSC). Concurrent with these developments was the design and launch of the CZCS on Nimbus-7 in late 1978. The CZCS data set provided very limited global coverage, but quite good coastal coverage of the U.S, in particular. The CZCS data set demonstrated that high quality open ocean pigment concentrations could be derived from space. The main limitation of the mission was the lack of an ongoing calibration and validation program to track sensor degradation (roughly 50% at 443 nm by the end of the mission). The CZCS failed in 1986 after nearly 8 years even though it was originally designed as a 1-year proof-of-concept mission. The entire data set was reprocessed at GSFC, in collaboration with the University of Miami, in the late 1980's and made available from the GSFC DAAC. It would be eleven years before another ocean color data set, SeaWiFS, would be available.

Even though the CZCS was launched in 1978, airborne system development continued, not only for active systems, e.g., the Advanced Visible and Infrared Imaging Spectrometer (AVIRIS), but also lidar systems. The primary lidar system for ocean applications, the Airborne Oceanographic Lidar (AOL), began as a bathymetric lidar activity at NASA/WFF in the 1970's. The system has been continually improved and used in numerous oceanographic experiments, e.g., the Warm Core Rings Experiment and several JGOFS field campaigns (North Atlantic, Equatorial Pacific, and the Arabian Sea), since the late 1970's. The AOL measures the fluorescent emissions of various pigments when excited at the laser wavelength and has been augmented with passive radiometry capabilities.

In 1997, Orbital Sciences Corporation (OSC), under a five-year data buy contract with NASA, launched SeaWiFS. Under this contract, OSC owns and operates the spacecraft and NASA provides science quality data for research purposes to the user community at no charge. Inherent in NASA's responsibilities is a robust and ongoing calibration and validation program and a data production system that can provide near realtime data and periodic reprocessings of the entire data set. The user community is also provided with user-friendly interactive processing software (the SeaWiFS Data Analysis System, SeaDAS), to generate all products (level-1, -2, -3). The SeaWiFS mission has been exceptionally successful in providing data, documentation, and services to the research community. The contract expires at the end of 2002 and an extended mission is being considered.

In late 1999, the EOS Terra platform was launched carrying MODIS which incorporates capabilities beyond SeaWiFS, e.g., solar-stimulated chlorophyll fluoroescence. The second MODIS on the EOS Aqua platform is scheduled for sometime in late 2002. Analyses of data coverage from different combinations of imagers at various overpass times show that three satellites provide optimal data when sunglint, cloud cover, scan geometry, and solar elevation are considered. MODIS (Terra), SeaWiFS, and MODIS (Aqua) have 10:30, 12:00, and 2:30 equatorial crossing times. Also, SeaWiFS is the only instrument that changes tilt each orbit to avoid sunglint. The combination of coverages from the three sensors should provide superb coverage on a daily basis, but requires highly accurate cross-calibrations.

The issue of deriving long-term consistent data across satellite platforms has nagged earth sciences for years, the AVHRR visible bands for NDVI being a good example. With multiple U.S. and international ocean color missions planned beginning in 1996, NASA initiated SIMBIOS in early 1997. The SIMBIOS Project Office is co-located with the SeaWiFS Project Office at GSFC and is working closely with the Japanese, French, European, Taiwanese, and

Korean space agencies on calibration and validation activities. The SIMBIOS Project has an international science team of about 65 members and works closely with the International Ocean Color Coordinating Group (IOCCG).

Physical oceanography measurements

Physical processes such as surface wind stress, surface heat and CO_2 fluxes, horizontal and vertical advection and mixing, play a critical role in the carbon cycle via their influences on the carbonate chemistry and biological processes in the ocean. NASA has pioneered the development of many satellite measurement technologies for physical oceanography applications which provide essential information for carbon research. These include high resolution infrared radiometers (e.g., AVHRR), altimeters (e.g., GEOS-3, SEASAT, TOPEX/Poseidon), microwave radiometers (SMMR), and scatterometers (SEASAT, Nscat, and QuikScat). NASA has also pursued other ocean-related technologies which do not have immediate application to carbon research such as synthetic aperture radars (SAR; SEASAT) and ice properties (cover, type, age, and thickness) from passive microwave sensors like the Nimbus-7/SMMR.

Early visible and infrared imagers on both sun-synchronous and geostationary platforms were developed for meteorological applications, but applications, especially in the infrared, were found in the 1970s as features such as the warm Gulf Stream could be easily identified. These instruments were first tested on NASA platforms such as the TIROS and Nimbus series and later transitioned to NOAA. Reasonable SST values were first obtained from the NOAA-6/VHRR, but the next generation AVHRR, developed at GSFC, on NOAA-7 included the split window bands around 12-13 microns which provided for atmospheric water vapor correction and much more accurate retrievals.

Simultaneous to the development of infrared sensors, passive microwave instruments were also being developed at GSFC. Early versions were flown in the 1970s and used to measure polar ice extent. The SMMR on Nimbus-7 was a major step forward and provided not only ice properties, but also a SST, albeit at coarser resolution than AVHRR. The advantage of microwave instruments is that they are relatively unaffected by cloud cover.

Altimetry measurements of sea level can be used to derive the oceanic geostrophic circulation, planetary wave propagation properties, and eddy kinetic energy and the return pulse shape can be used to estimate significant wave height. In certain locations such as the equatorial Pacific, sea level can be related to the depth of the thermocline. Early spaceborne altimeters were flown on the Geodynamics Experimental Ocean Satellite (GEOS)-3 and SEASAT. NASA WFF pioneered this development and continued design refinements using airborne systems throughout the 1970s. Beginning with a third generation altimeter (SEASAT launched in 1978), JPL has had the lead in altimetry mission management with scientific and technical support from GSFC and WFF. SEASAT suffered an electrical system failure after three months, but the altimeter data proved to be a significant improvement over GEOS-3. Altimetry continued throughout the 1980s under the U.S. Navy Geosat program. The most recent mission, TOPEX/Poseidon, a joint NASA collaboration with the Centre National D'Etudes Spatiales (CNES, the French space agency), was launched in 1992 and continues to provide superbly accurate global sea level data.

The measurement of surface winds using airborne and spaceborne radars was pioneered at the LaRC. The first spaceborne scatterometer was tested on Skylab and a second generation instrument was on SEASAT. The SEASAT data proved a striking confirmation of the scatterometry technique, but the next NASA scatterometer mission would not be until 1996 on

the Japanese Advanced Earth Observing Satellite (ADEOS)-I platform. ADEOS-I suffered a power system failure after about 8 months, but, in 1999, NASA launched the QuikScat mission, managed by JPL, minimizing the lapse of coverage. QuikScat continues to provide high resolution, high quality vector winds. During the hiatus between scatterometry missions, much progress was made in deriving wind speed from passive microwave sensors such as the Nimbus-7/SMMR. Wind speed data from passive microwave sensors have been combined with information from atmospheric models to obtain high quality vector winds.

Research and development

Throughout the 1970s, funding for oceans research within NASA was distributed across several sources. In the early 1980s, a formal oceans program was formed with program managers for physical, biological, and polar oceanography. Since then, the oceans program management has experienced several reorganizations, but has maintained its integrity as a program. During the 1980s and most of the 1990s, the ocean biology program focused on demonstrating that ocean color was indeed quantitative, on exploring the various applications of the CZCS data set, and on getting CZCS follow-on missions approved and launched, e.g., SeaWiFS and MODIS. The program maintained a remote sensing component in the JGOFS field experiments, usually by funding AOL flights, given that delays in the SeaWiFS launch precluded satellite coverage of the Arabian Sea, and equatorial Pacific field programs. However, unlike the NASA terrestrial research program, the ocean biogeochemistry program has not undertaken large remote sensing intensive field studies such as the terrestrial program's FIFE and BOREAS. There were some field experiments of this nature in the late 1970s, e.g., Superflux, a study of the Chesapeake Bay conducted by LaRC, but nothing similar since then. The wave tank facility at WFF, originally designed for surface wave generation, wave-current interaction, and surface slope distribution studies for remote sensing applications, has been used recently for air-sea gas flux studies.

Early analyses of the CZCS data revealed far more mesoscale biological variability in both coastal and open oceans than had been previously appreciated. The data also highlighted the diversity of physical processes that could generate this variability and underscored the necessity of combining the satellite data with coupled biological-physical models to derive adequate explanations of the variability. Within NASA, this type of coupled modeling began in earnest at GSFC in the early 1990s using both 1-D and ocean general circulation models. In the late 1990s, NASA provided additional funding for coupled ocean biological-physical modeling and data synthesis studies as part of the National Science Foundation JGOFS modeling and data synthesis program. Today, these models include various combinations of phytoplankton, zooplankton, macronutient, micronutrient, Fe, and detrital components as well as carbon chemistry. Aside from computational constraints, ocean biogeochemical models are generally limited by a lack of understanding of many basic processes such as species succession, micronutrient recycling, and nitrogen fixation, although the models can reproduce the observations quite well in some regimes such as the subpolar North Pacific.

Ocean circulation modeling at GSFC began in the late 1970s, primarily for the tropical oceans, primarily to study the ENSO cycle and the tropical Atlantic in the early 1980s as part of the international Francais Ocean et Climat dans L'Atlantique Equatorial/Seasonal Response of the Equatorial Atlantic Experiment (FOCAL/SEQUAL) program. In the early 1980s, JPL became the lead center for physical oceanography as preparations for Nscat and TOPEX/Poseidon began. As a result, ocean circulation modeling became part of the program at

JPL as well. By the late 1980s, modeling in the polar and mid-latitude oceans was underway including ice models. In most cases, these models have focused on the response of the ocean to given meteorological forcing, but more recently, coupled atmospheric-ocean models have been developed. In some cases, the coupled models consist of an ocean circulation model coupled with an atmospheric boundary layer and specified forcing above the boundary layer. The main limitation is the considerable computational requirements for fully coupled modeling. These model development activities over more than twenty-five years lead to the initiation of NSIPP at GSFC in the late 1990s which seeks to link ocean, atmosphere, and terrestrial (hydrologic) models with satellite ocean and land data assimilation capabilities to provide improved forecasts.

Distributed satellite data analysis software support

Although the CZCS was a proof-of-concept mission, the long delay between its launch and the community's ability to utilize the data was the result of several limitations including the following:

1) robust atmospheric and bio-optical algorithms were not available until several years after launch,
2) the validation program was only funded at a significant level for the first year after launch which did not allow for a comprehensive evaluation of the sensor's performance on orbit,
3) the original data processing requirement was only 10% of the data collected and there were no plans for routine analysis, periodic reprocessing, and distribution of the data, and
4) processing software was not available to the user community.

The SeaWiFS program, in particular, has been able to address all these deficencies, In the case of MODIS, (1) and (2) have been emphasized by the MODIS team, but items (3) and (4) involve components of the EOS Data and Information System (EOSDIS) that have not yet achieved those objectives. In the case of the CZCS, user-friendly processing software was developed independently at GSFC (SEAPAK) and the University of Miami (DSP) as part of individual NASA-supported P.I. research programs. By the late 1980s, both software packages were available to the user community. When the SeaWiFS program was approved, the GSFC group discontinued the development of SEAPAK, although user support was continued for several additional years, and focused on the development of SeaDAS. The intent behind SeaDAS was to provide the research community with user-friendly workstation-level processing software that could duplicate all the Project's archive products. The NASA ocean biogeochemisry program has supported SeaDAS since 1991 when the SeaWiFS Project was formed. SeaDAS also supports the processing of data from other ocean color missions such as the ADEOS-I Ocean Color and Temperature Scanner (OCTS), the Indian Remote Sensing satellite (IRS)/P-3 Modular Optoelectronic Scanner (MOS), and CZCS, as well as the display of MODIS ocean products. SeaDAS is distributed free of charge and is being used by more than 800 user groups in over 45 countries.

A2.3. Atmospheres Summary

NASA has made major contributions to research in the atmospheric components of carbon cycle science through modeling and measurements. This experience combined with current and planned programs puts NASA in a strong position to initiate a new program focused specifically on carbon. There has been a significant effort in climate modeling and predicting carbon-climate interactions that is directly applicable to carbon cycle questions over a range of time scales. There is also significant ongoing and planned work to integrate the atmosphere with

land and ocean process models including the effects of biomass burning on the atmosphere. These activities are proceeding toward model assimilation of atmospheric constituent measurements from EOS and other observations. Further, NASA has been, and will continue to be, a major contributor to advances in modeling and measurements for global atmospheric chemistry and aerosol processes including satellite remote sensing and validation. Research on atmospheric chemical tracers and reactive species includes CO and CH_4, but has had limited focus on CO_2 sources and sinks. Atmospheric chemistry sources, sinks, and transport are, however, directly related to carbon cycle questions. The following discussion represents past, current, and future NASA efforts planned for the next approximately 2 years, irrespective of the GCCP. Underlying this discussion is an assumption that the key problem is to determine the past and future sources and sinks of atmospheric CO_2 and the processes that control them.

Atmospheric chemistry and aerosol process studies and programs

NASA has historically taken a leading role in measurements and modeling of tropospheric CH_4, CO, hydrocarbons, SOx, NOx, O_3 and other chemicals, primarily for understanding the role of atmospheric chemistry in global change. Results from this program are directly and indirectly related to carbon cycle. The aircraft field campaigns of the Global Tropospheric Experiment (GTE) have addressed emissions and long-range transport of pollutants and led to fundamental understanding of chemical processes. The GTE missions have measured CO and CH_4 fluxes and atmospheric chemical transformations from biomass burning and natural systems in tropical oceans, rainforest, and northern wetlands. Biomass burning impacts on the atmosphere are an important component of the NASA programs. CO_2 measurements are routinely made from the aircraft during field campaigns, although mainly for use as a transport tracer, not for source/sink estimation. Aerosol measurements are also included.

Complementary to the satellite and field measurement programs, NASA has developed a program for data analysis and modeling of tropospheric chemistry and transport that is applicable to carbon modeling and analysis. Part of this program is the Global Modeling Initiative (GMI), a chemical transport model evaluation and assessment tool. GMI serves as a community-based test bed for algorithm and input data evaluation in a consistent framework that will lead to a better understanding of global chemistry-transport model sensitivity and uncertainty, and hence to improved simulations and predictions.

NASA has also established the Global Aerosol Climatology Project to analyze satellite radiance measurements and field observations in order to infer the global distribution of aerosols, their properties, and their seasonal and interannual variations; and to perform advanced modeling studies of the aerosol formation, processing, and transport. The resulting datasets and analysis products are used to improve the understanding and modeling of the climate forcing due to changing aerosols, including both the direct radiative forcing by the aerosols and the indirect radiative forcing caused by effects of changing aerosols on cloud properties. A 20-year global climatology will be compiled for use in climate models. The aerosol data set and eventually the aerosol radiative forcing data set will be based on multiple satellite data streams, a combination of satellite and aerosol tracer model results, surface-based aerosol measurement networks, field observations, and other data.

Atmospheric remote sensing

With the arrival of the EOS era, NASA delivers a far-reaching program of atmospheric measurements, many of which are relevant to carbon cycle processes. This includes

measurements of temperature, water vapor, precipitation, cloud properties, aerosols, radiation, and chemical constituents with unprecedented coverage and accuracy. Many of these data will pervade carbon cycle analyses as they affect carbon processes either directly or indirectly. Here we discuss those constituent measurements expected to be directly important to atmospheric carbon cycling.

EOS will provide global measurements of atmospheric CO and CH_4 in the troposphere from the MOPITT and TES instruments. The MOPITT instrument follows a heritage from the Measurement of Air Pollution from Satellites (MAPS) instrument that measured tropospheric column (3 to 10 km) CO on several shuttle flights from 1981 to 1994. MAPS produced the first near-global maps of pollution in the troposphere. The data have been used to identify industrial and biomass burning source regions along with transport and chemical removal timescales and processes. MOPITT data will provide global coverage of column CH_4 and CO with some altitude discrimination in the troposphere at better accuracy than MAPS. TES will improve further on the measurement of these important constituents with better coverage, accuracy, and vertical resolution. TES will measure tropospheric CO and CH_4 profiles as standard products along with a variety of hydrocarbons and many other species as special products. In addition, theAura/Microwave Limb Sounder (MLS) will measure CO and the Aura/High Resolution Dynamics Limb Sounder (HIRDLS) will measure CH_4 in the stratosphere and upper troposphere. The satellite constituent measurements are supported by an extensive validation program. Validation activities include comparison to regular ground based, aircraft, and balloon data as well as science validation missions. Although high-precision atmospheric CO_2 measurements are not a primary satellite data product from any of the existing sensors, CO_2 measurements are being augmented through the validation program. For Terra, this includes regular light aircraft CO, CH_4, and CO_2 profiles at several sites to define the temporal and vertical variation of carbon gases above the planetary boundary layer; deployment of ground based instruments for CO and CH_4 validation by a variety of remote sensing techniques; analysis of biomass burning regions and emissions of aerosol, CO, CH_4, and CO_2; and FLUXNET validation data including CO_2 fluxes and a flux data information system. The Aura validation plan is currently in the formulation stage, but it will certainly include careful evaluation of Aura constituent data explicitly for application to key science problems including carbon cycle processes.

The Atmospheric Infrared Sounder (AIRS), Advanced Microwave Sounding Unit (AMSU), and Humidity Sounder Brazil (HSB) will be launched on the EOS Aqua platform in 2002. With the broad spectral coverage of AIRS (649-2700 cm^{-1} or 3.7-15.4 um) and of AMSU/HSB (23-190 GHz), the AIRS/AMSU/HSB system is uniquely capable of obtaining global measurements for simultaneous knowledge of the atmosphere, surface, and clouds. Information from all three instruments is used to produce the "AIRS" products. Simulation of AIRS/AMSU/HSB radiances have been used to assess the possibility of adding atmospheric CO_2, CH_4, and CO retrieval products to the standard set of products for clear scenes. Preliminary results demonstrated that retrieval of trace gases from simulated AIRS clear spectra could be done with RMS errors of 0.9% (3 ppmv) for CO_2, 1.3% for CH_4, and 15% for CO with some vertical information per AMSU field-of-view. The bulk of the AIRS signal for all three of these gases come from the 200 to 800-hPa region of the atmosphere. The vertical information within this layer can be improved, possibly separating the upper and mid-troposphere to a large degree. AIRS trace gas retrieval uncertainties are expected to improve via optimal utilization of the AIRS spectrum in the retrieval process. Gridded products of these AIRS trace gas products will have higher accuracy and will complement other products (in-situ, MOPITT, etc.) already in

use to answer questions about sources and sinks of these gases. At this time, we are unable to estimate the accuracy of an AIRS gridded product, since the correlation of retrieval errors is poorly understood for this product. Validation plans for Aqua AIRS constituent data have not yet been formed, as these data are currently developmental products.

AIRS has a unique benefit of simultaneous measurements of other components of the geophysical state: temperature profile (T(p)), moisture profile (q(p)), ozone profile (O_3(p)), surface skin temperature (T_s), spectral surface emissivity (both infrared and microwave), spectral surface reflectivity, surface NDVI (from AIRS visible channels), cloud fraction and cloud top pressure for multiple cloud layers, as well as derived products of outgoing long wave radiation (OLR) and clear sky OLR. These components of the geophysical state will be useful in several ways. For CO_2, the knowledge of temperature and water is crucial, as is a knowledge of the contamination of the scene by clouds under clear conditions. AIRS temperature and moisture products are expected to be extremely good (~ 0.5 K/km layer, ~ 5%, respectively) and we expect to have an extremely robust clear flag at the end of the retrieval process. Also, regional soil moisture and phase (ice, snow, water) can be estimated by the microwave instruments on Aqua. This should complement the CO_2 product for terrestrial process models. Furthermore, the AIRS trace gas products have the potential to be a longer-lived product set. Follow-on instruments are the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Cross-track Infrared Sounder (CrIS) and NASA's Advanced Technology Microwave Sounder (ATMS), which will have very similar capabilities to AIRS/AMSU/HSB.

Linking atmospheric and land/ocean surface process models

The NASA ESE has a rich history and substantial ongoing activity in linking the atmospheric state to land and ocean process models including those that simulate carbon cycling processes. Much of this support has come through the EOS Interdisciplinary Science (IDS) program, which addresses many aspects of carbon cycle modeling and analysis.

An important area of research is atmosphere-biosphere interactions with the goal of improving the representation of land processes in climate models by application of EOS observations. Coupled biosphere-atmosphere models, e.g., Simple Biosphere (SiB)2-General Circulation Model (GCM) have been constructed, implemented, and tested. Carbon dynamics and tracer models are being included to investigate the impacts of climate on carbon and localize variations in carbon sources and sinks. AVHRR NDVI data are processed for input and model evaluation. Studies of biomass burning effects on the atmosphere include carbon emissions and carbonaceous aerosols. The analyses aim is to obtain convergence of top-down and bottom-up approaches to quantifying terrestrial sources and sinks of carbon. Biosphere-atmosphere field measurement campaigns are an important element to achieving this convergence.

Coupling of atmosphere-ocean process models include model studies of dust transport and Fe deposition flux and the use of the Total Ozone Mapping Spectrometer (TOMS) data for validation. The atmospheric transport of iron-containing dust and deposition to the ocean is important to marine photosynthesis, and hence carbon uptake, in some locations (e.g. the Southern Ocean).

In concert with the coupled model development, data assimilation techniques for ocean, land surface, and tropospheric chemical data are being developed. These methods in combination with new data sources will allow us to better constrain and understand the complex interactions of coupled systems, which will lead to better understanding and predictability of climate-carbon interactions.

Global climate modeling related to the carbon cycle

Global climate modeling aimed at decade-to-century time scales is central to carbon cycle issues. NASA has supported such work at the Goddard Institute for Space Studies (GISS) and other institutions since the late 1970s. However, the demands on the global models for carbon cycle science have become considerably more complex. Now, rather than using specified scenarios for atmospheric composition, it is necessary to use scenarios for anthropogenic and natural emissions, and use models to simulate both atmospheric and climatic outcomes of those emissions. This capability is required in order to assess the impact of alternative policy scenarios on future trends of climate forcings such as atmospheric CO_2 and CH_4.

There is a current focus at GISS and elsewhere on the longer-term interplay between climate and carbon, specifically the atmospheric budgets of CO_2 and CH_4. Their concentrations will vary not only as a function of anthropogenic emissions, but also because of climatically controlled variations in the important sinks (the land biosphere and oceans for CO_2, and tropospheric chemistry for CH_4) and natural emissions (e.g., CH_4 from wetlands). State-of-the-art climate modeling now includes many of these components (for example, tracer transports in the ocean and atmosphere, carbon fluxes from the land surface, tropospheric and stratospheric chemistry, data-sets of CO_2 and CH_4 emissions). However, there are other key components of the carbon cycle modeling that are not completed and do not have identified funding sources.

For the GISS climate model, three additional components are required to have the nucleus of a fully interactive carbon cycle within the atmosphere-ocean-land coupled model. These are: (1) coupling of a mechanistic model for wetlands methane emission anomalies, (2) introduction of interactive vegetation dynamics, and (3) the inclusion of the various carbon pumps within the ocean component. Projects 1 and 2 will be able to draw on in-house expertise for their completion, while including the ocean carbon system would be most easily accomplished through collaboration with the team at GSFC. It will be necessary to coordinate and integrate some of these disparate modeling initiatives so that all of the carbon cycle related components can be run together.

Although there are some missing pieces in the NASA GISS modeling that will need to be completed for successful carbon-climate studies, we note that there are some areas in which GISS is well poised to make contributions. GISS has pioneered, and continues to be at the forefront of modeling stable isotopes (such as ^{18}O) within the hydrologic cycle. The isotopic signature of the oxygen within CO_2 has become an important tracer of carbon fluxes, and this signal ultimately depends on the isotopes in surface ocean seawater. Thus, there may be a fruitful interaction between this GISS modeling effort, the inversion models that use $C^{16}O^{18}O$ data, and the remote sensing of $C^{16}O^{18}O$ concentrations. Note also that wind fields from the GISS GCM runs have been widely used "off-line" in CO_2 source/sink inversion studies.

Data assimilation

Currently, NASA support two major data assimilation activities, both at GSFC, the NASA Data Assimilation Office (DAO) and the NASA Seasonal to Interannual Prediction Program (NSIPP).

NASA Data Assimilation Office (DAO)

The DAO has recently undergone a major change of direction, through successful collaboration with the Climate Modeling group at the National Center for Atmospheric Research

(NCAR). In this collaboration, a state-of-the-art dynamical core (developed in the DAO) has been coupled to the parameterizations of physical processes from the NCAR Community Climate Model (CCM). The first version of this model, based on CCM3 (version 3), is operational and shows many improvements over the previous atmospheric GCM used in the DAO. These improvements include a much better representation of trace gas transport, which is of special significance for studies of the carbon cycle, and a much smoother representation of the atmosphere. The principal goal of the modeling effort in the DAO is to provide the best possible first guess field for data assimilation (the combination of model forecasts with observations). In the free atmosphere, the data assimilation system based on the DAO-NCAR model shows many improvements over the present operational system, particularly a reduction in the noise of the assimilated products.

For future developments, the collaboration with NCAR offers many benefits. First and foremost, model development at NCAR is based on a large team of researchers, which has links with several university groups. This gives access to the most up-to-date parameterizations for testing and eventual inclusion in future model versions, if they turn out to be more realistic than current representations. Research areas crucial to carbon science, which will benefit greatly from the collaboration between DAO and NCAR, are the land surface modeling and the treatment of the atmospheric boundary layer. Future developments of the land surface model are being performed in a national framework, in which NASA GSFC scientists are also participating. Close collaboration between DAO and NCAR in these (and other) areas represents not only a mechanism of collaboration between NASA and the national modeling community; it also opens up possibilities for pushing frontiers of research at the interface between the atmosphere and the land surface, which is of prime importance to the carbon cycle.

One of the main advantages of the DAO dynamical core over all other dynamics/transport schemes presently in use is the accuracy of the trace gas transport in this scheme. The DAO is presently developing its ability to model and assimilate a wide range of trace species, ranging from ozone to carbon monoxide and methane. These latter species are being observed by NASA's EOS program of measurements and the DAO is already performing or collaborating on studies to model and assimilate them. The scientific methods used with these trace gases can be applied to CO_2. A comprehensive modeling and assimilation program would be developed in the DAO in support of GCCP. This will require a dedicated effort, with emphasis on the development of the model and on the interfaces between the model and the data, with particular emphasis placed on the utility of certain types of data sets to the assimilation process. Frameworks to determine the usefulness of particular data sets to the assimilation process either exist or are being developed at NASA, and these would be applied to projected observations of carbon species. In this way, the DAO model tests will provide feedback on the potential uses of passive or active measurements of carbon dioxide in the atmosphere. Such work requires close collaboration with instrument teams in the development phases of planned missions.

NASA Seasonal to Interannual Prediction Program (NSIPP)

The goal of NSIPP is to develop an assimilation and forecast system capable of using a combination of satellite and in situ data to improve the prediction of ENSO and other major seasonal-to-interannual signals and their teleconnections. In addition to producing experimental forecasts, NSIPP is involved with a variety of cutting edge seasonal-to-interannual research issues. Given NSIPP's main goal of developing a forecasting system, much of the research

focuses on issues that are addressed through use of NSIPP's coupled and component models, and the ocean and land data assimilation systems being produced. NSIPP's coupled GCM employs the Goddard Earth Modeling System (GEMS) to couple the atmospheric, ocean and land models. The land/ocean mask for the coupled model is defined on the ocean's latitude-longitude grid, so each grid box is either all ocean or all land. The atmosphere to ocean couplers interpolate from the atmospheric grid to the mass point of the underlying ocean boxes. The implementation assumes the ocean grid boxes do not straddle the atmospheric grid boxes. In the atmosphere to ocean coupling, interpolation consists of replication of the atmospheric values at each of the underlying ocean grid boxes. In the ocean to atmosphere coupling, interpolation consists of averaging together the underlying ocean grid boxes. The ocean model controls the evolution of all non-land surfaces, i.e., open ocean, shallow seas and sea ice. Inland lakes are treated by the atmosphere as land surfaces. The coupling between the land and the atmosphere is handled in a similar fashion.

NSIPP runs its fully coupled global ocean-atmosphere-land model initialized with NSIPP analyzed ocean states to produce 12-month forecasts of the coupled system. The ocean assimilation/analyses are currently restricted to the tropical Pacific, so the main product from these forecasts, referred to here as Tier 1 forecasts, is tropical Pacific SST anomalies. Niño-3 (90°W-150°W, 5°S-5°N) is chosen as the area for presentation as it is the area where the effects of El Niño and La Niña are often strongest. NSIPP also runs an ensemble of its coupled land-atmosphere model with prescribed SSTs provided by adding the observed climatology to anomalies from the appropriate Tier 1 forecast as forcing. These 3-month forecasts, referred to here as Tier 2 forecasts currently represent the global response in the atmosphere and land to forcing by Pacific SST anomalies.

A2.4 Data and Information Systems

NASA's charter has required the ESE over the years to develop data and information approaches that can handle large volumes of very complex, interdisciplinary data sets. Global satellite observations are voluminous, and periodic reprocessing of these data are necessary as new and improved products and algorithms are developed.. This global data handling requirement has driven the development of not only computing systems, but the expertise to use those computing systems to produce earth observations from the raw satellite data, to support complex interdisciplinary oceans, atmosphere and land process models, and to archive and distribute large volumes of data. Through projects such as the data pathfinder program and DAACs, NASA has accumulated a global archive of climate, oceans, land, ice and snow data and the capabilities to acquire, store and distribute such data. Through its many satellite projects, NASA has learned to acquire, navigate, and calibrate satellite data and to produce useful data products such as land cover, SST, ocean chlorophyll and other data needed to support GCCP. Thus, after nearly 30 years of developing such data and information systems, NASA well-positioned to support a complex research prorgam such as the GCCP.

APPENDIX 3. NEW OBSERVATIONS AND MODELING REQUIREMENTS

A3.1 Atmospheric CO_2

Observations

The major limitation to reducing the uncertainties in the location and magnitude of sources and sinks is the sparseness of atmospheric CO_2 observations. Open oceans and continental interiors are especially under-sampled. A high-priority goal of the GCCP is to

exploit fully the existing capabilities both from surface and space platforms and to develop new technologies for measuring atmospheric CO_2 concentrations from space at sufficient temporal and spatial resolutions to enable inverse models to accurately locate and quantify sources and sinks at spatial resolutions that will allow identification and quantification of important carbon source/sink areas.

The scientific measurement requirements for atmospheric CO_2 include seasonally resolved, global coverage, on a regional spatial scale (order of 1000 km^2). Satellite remote sensing is the only practical approach given this spatial requirement. The main technological challenge is accuracy. Inferring fluxes from concentration measurements (used as inputs to inverse models) requires a precision on the order of 1% of the CO_2 concentration (± 1 ppmv) or better to improve our estimates of the surface flux distribution significantly. Bias (accuracy) errors would need to be at a similarly low level. These accuracy requirements are more stringent than any current or planned satellite instrument for measuring atmospheric constituent distributions. Consequently, the requirements for measuring the variability of atmospheric CO_2 include key investments in technology development, algorithm development, and in situ and ground-based measurements aimed at improving our ability to remotely sense CO_2.

Instrument concepts

Numerous approaches exist for remote sensing of CO_2 in the atmosphere, and in fact, CO_2 is routinely measured, albeit at low precision, as a means of calculating atmospheric temperature. However, since CO_2 variability in the atmosphere is driven by processes at the Earth's surface, most of the variability in CO_2 concentrations exist in the lower atmosphere, i.e., primarily in the planetary boundary layer (~1-2 km). The need for a space-based sensor to resolve variations near the surface, the ubiquitous presence of clouds in the atmosphere, and the stringent accuracy and precision requirements to meet the needs of inverse modeling approaches combine to limit the range of viable measurement techniques. Currently, the most promising techniques for obtaining the performance needed to resolve regional carbon sources and sinks involve measuring the absorption of near-infrared light by CO_2 from low Earth orbit (LEO) with a near-nadir view over a small ground footprint (to avoid cloud complications). One proposed configuration would measure total column CO_2 using reflected sunlight in a concept similar to the one employed by the TOMS instrument. Variability in the total column CO_2 is strongly weighted to the lower atmosphere because of the exponential decrease of atmospheric density with height. Another concept would use a space-based laser for the light source. The laser method holds the possibility of resolving the CO_2 in the lower atmosphere separately from the overlying CO_2 in the upper atmosphere, which would improve sensitivity, but requires significant technology development. A sound strategy would be to evaluate a passive (solar illumination) system for deployment in the 5 to 7 year time frame while exploring the pathway toward development of a more fully capable active (laser) system for deployment at a later date. A decision could be made in a 3-5 year time frame as to which approach would be sufficient to meet the scientific requirements for atmospheric CO_2 and be most cost-effective. A decision to pursue both, if the scientific need and policy urgency is sufficiently compelling, would be an option as well. Continuous refinement of the science measurement requirements, technology and algorithm development, and better process understanding will lead to an evolving assessment of the most effective measurement approach for obtaining critical atmospheric CO_2 data.

The extremely demanding accuracy and precision requirements (less than 1% CO_2 concentration) for measuring atmospheric CO_2 drive the program plan to develop the

observational capacity. Technology development is needed, particularly in active (lidar) systems to push current optical detection methods to an increased level of accuracy and precision and to ensure laser reliability. Active methods also require improved laser power and control at the component level. The development path starts with laboratory bench demonstrations, which are currently underway, through ground-based and aircraft instruments to simulate sensor performance and the data, and up to space. Deployment of ground-based and airborne remote sensing instruments will be key to demonstrating system performance. They will also provide real data for retrieval algorithm development and the opportunity for direct comparison with highly accurate in situ measurements. Furthermore, these measurements could have immediate scientific benefit, adding unique and valuable spatially integrated CO_2 information for process studies and field campaigns. These instruments could later serve to calibrate and validate the space systems after launch. Through the GCCP, these technology development activities can be implemented through NASA program structures such as the IIP.

The ultimate precision for measuring CO_2 will depend on the performance of the instrument system, and on our ability to isolate the variability of the observed signal due to CO_2 from that due to variations in clouds, aerosol, temperature, pressure, other absorbing molecules, surface reflectivity, and possibly other interfering or confounding variables. Again, the stringent error requirements for CO_2 dictate that we must be able to account for other variables to a very high degree of precision and accuracy in the CO_2 retrieval algorithm. The development program for the CO_2 algorithm will require laboratory spectroscopy, analysis of ground-based and aircraft remote sensing CO_2 data (as above) in conjunction with in situ measurements of CO_2 and associated state variables, and new retrieval methodologies. Analysis of existing and planned satellite remote sensing data applicable to CO_2, such as the Aqua/AIRS, ENVISAT/Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY), and Aura/TES, will be very beneficial, although these sensors were not designed specifically for CO_2.

Achieving the goal of identifying and quantifying sources and sinks using satellite CO_2 data will require an extensive program of field measurements for process studies (e.g., boundary layer growth and decay) and calibration/validation of satellite measurements. In particular, the remote sensing data must be connected to the long-term record of surface CO_2 data from the NOAA Climate Monitoring and Dynamics Laboratory (CMDL) measurment network, the continuous CO_2 flux records of DOE's AmeriFlux and the international FLUXNET networks, and USDA's forest, cropland, and soil inventories. Conceptual and practical methods for scaling up from local site data to global remote sensing will be developed through intensive field campaigns and systematic deployment of in situ measurements, e.g., aircraft profiles, to cover a broad spectrum of biophysical and biogeochemical conditions. The NACP will provide an opportunity and context for many of these studies.

A3.2 Biomass, Biomass Change, Terrestrial Ecosystem Disturbance and Recovery Observations

Climate predictions can only be made with confidence when the mechanisms for terrestrial carbon uptake and storage are identified and their dependence on external influences established, specifying how sink strengths will depend on climate variability, human actions, and other environmental forcings. Current estimates of carbon storage in terrestrial ecosystem biomass are uncertain by 25% or more. Estimates of the U.S. component of the North American sink based on ground inventories are uncertain by 50% even though these studies show that the

U.S. may account for about 60% of the North American carbon sink. Ground inventories, based on harvesting and weighing all vegetation, are labor-intensive, and thus have been confined to a very sparse sample, and extrapolated using land cover information. These samples are neither sufficient nor representative, and the sampling is known to be biased in favor of timber production lands and accessible sites near roads or rivers. Further, we have little understanding of the magnitude and rate of biomass loss due to disturbance or accumulation in re-growing, recovering vegetation or their implications for regional or global carbon budgets. The primary accumulation and storage mechanisms for terrestrial ecosystems are in living plant biomass, about one-half of which is carbon, and soil organic matter. Plant support structures are continuously accumulating and storing carbon at different time scales. Trunks, branches, stems and coarse roots can accumulate and store carbon over years to decades and are slow to decompose. Twigs, leaves, fine roots, and most animals, bacteria, and fungi recycle their carbon more rapidly. Rates of release are affected by human activities, such as logging, land use, and land management practices such as fire suppression. Regrowth is affected by variations in climate, fertilization effects from increasing atmospheric CO_2 concentration, atmospheric nitrogen and deposition of other products of combustion.

The largest source of short-term change in biomass is land cover change, including biomass destruction and carbon release due to logging, land use conversion, and fire, and carbon uptake and biomass accumulation due to vegetation recovery in the first few years following disturbance. Disturbance often occurs at length scales of a few tens of meters or less, well below the spatial resolutions of the sensors aboard EOS Terra. The 30 meter resolution mapping capability of Landsat is better suited to detecting and measuring the areal extent of this disturbance, as well as the cause. To measure the recovery rates however, Landsat is limited. Height and structure information of the type now available from airborne lidar and radar sensors can be invaluable for characterizing recovery. Thus, there is a critical synergy between the land cover information available from Landsat, and the height and structure information available from lidar and radar. Land cover maps derived from passive optical imagery provide the regional context for interpreting biomass change, distinguishing between transient reductions in biomass associated with burn events and permanent land-cover conversion associated with human activities, while lidar and radar can provide the rate of recovery from disturbance. In addition, knowledge of the type of land cover is also necessary to convert canopy height into biomass information. The 30-year Landsat record provides an historical context for converting short-term biomass measurements into medium-term trends in carbon accumulation and release.

Instrument concepts

Airborne lidar measurements of profiles of forest canopy height, when combined with land cover information, have demonstrated an important new capability for estimating forest biomass. A vegetation canopy lidar (VCL) satellite is near completion now, but there are technological readiness concerns. When these concerns are resolved, this mission will provide the first internally consistent global estimates of forest biomass based on a systematic sampling design. Use of this new capability could result in a reduction in errors in the current estimates of global terrestrial biomass from 25% to as little as 1%. Estimates of biomass change from this mission will be limited by its short duration, but the feasibility of measuring biomass change for future, longer duration or repeat missions will be evaluated. Developing algorithms to convert these canopy lidar data in combination with land cover maps to estimates of carbon stored in biomass for the full range of global ecosystems is an important task for the GCCP.

NASA's ESE base program is already funding the assembly of the global, Landsat record extending back to 1972 and, using manual methods will provide initial global land cover change maps from this period. To facilitate the routine analysis of these data, NASA will investigate the necessity and feasibility of transitioning to an automated processing capability for Landsat and possibly other sensors such as ASTER and MODIS. Such a system would need to allow on-demand analysis of geo-registered imagery to create a variety of land-cover products on a routine basis by 2005, ultimately at a substantial cost savings compared to the presently-used labor-intensive approaches.

Measuring structure and biomass change at accuracies of 0.5 to 1 kg m^{-2} and the 10 to 25 km scales required by the next generation of land surface models (~0.25° resolution) will require a different approach from that of the vegetation canopy lidar now in development. Alternatives include imaging lidar, hyperspatial/multiangular/hyperspectral optical imagery, interferometric SAR, and SAR combined with profiling lidar which have shown potential in model simulations and/or airborne demonstrations. Measuring biomass differences well in dense vegetation with canopies shorter than 5 m also presents a challenge for all these methods. Investments in transmitters and detectors for imaging lidar and antennas for P-band radar systems will help bring these technologies to a suitable level of maturity, comparable to space instrumentation for passive optical and shorter-wavelength SAR (C, L, and K band) observations.

Some representative options for biomass change measurements that will help us quantify the carbon impacts of disturbance and recovery in terrestrial ecosystems have been studied and costs estimated. Inter-comparisons of data acquired using existing airborne sensors will be used to assess performance of the most promising approaches, in field settings covering the required range of conditions. At a minimum, these will cover realistic observing conditions and a wide range of biomass densities in tall, dense forest, open woodland, closed shrub land, and dense grasslands and savannas. In some cases, new measure concepts may require the development of aircraft instrument prototypes, e.g. a dual frequency lidar. In a 5-6 year time frame, assuming a vegetation canopy lidar mission and airborne simulator sensor evaluation studies, NASA would be in a position to recommend the best option(s) for future biomass and biomass change observations that would be adequate to substantially reduce uncertainties in carbon sources and sinks due to disturbance and recovery from past disturbances.

A3.3 Ocean Carbon

Observations

The overall goal with ocean observations in the GCCP is to predict the variability of carbon (in its various forms) in the ocean, and thereby evaluate its role in climate change, and how that role might change under various climate change scenarios. The productivity, or photosynthetic carbon flux, on the land and in the ocean are of about the same magnitude. However the carbon biomass of the land is over two orders of magnitude higher than the ocean, thus, the ocean achieves the same photosynthetic flux with a much smaller biomass. It is clear, then, that the carbon cycle in terrestrial ecosystems is dominated by the storage in biomass, whereas in the ocean it is dominated by the flux. Space-based observation strategies for the ocean therefore need to include measurements, which can be used to estimate of the flux of carbon, however indirect, across the air-sea interface and through the ocean's ecosystems.

The two primary fluxes that the GCCP will need to characterize are the CO_2 flux across the air-sea interface and the export of carbon to the deep sea for long-term storage. Carbon export to the deep sea occurs as particle sinking (the "biological pump") and subsidence of cold

CO_2 -bearing water (the "solubility" pump). An additional carbon flux of interest is the particulate and dissolved organic carbon in terrestrial runoff. Schemes for estimating all of these fluxes will be developed using a combination of in situ and satellite observations and models.

Current remote sensing capability is focused on quantifying the photosynthetic flux, or productivity, of the ocean (supported by the ocean color sensors, SeaWiFS and MODIS). However, large uncertainties in air-sea fluxes of CO_2 and carbon export to the deep sea remain. The interaction between the solubility and biological pumps has never been established with the required spatial and temporal resolution at global scales to determine their role in climate change. For example, we know that air-sea CO_2 fluxes depend on surface CO_2 concentrations (which in turn depend on complex interactions between surface temperatures, biological production, surface carbonate chemistry, and ocean circulation) and on the CO_2 transfer efficiency at the surface (which is controlled by winds and ocean surface characteristics). But accurate prediction of carbon fluxes will depend on how well we can characterize these regulating processes and quantify their spatial and temporal variability. Likewise, the determinants to ocean productivity and the carbon deposition to the deep sea are complex and, in many regions, the models and satellite algorithms break down because we are missing critical information on phytoplankton physiology and the type of organisms present. More accurate estimation of marine carbon fluxes is critically needed to establish the present state of the marine carbon cycle and to forecast future responses and feedbacks to the climate system. Substantial process towards attaining these goals within the time frame of the GCCP (10 years) will only be achieved by accelerating and expanding our the observational and modeling capabilities.

One reason for the uncertainties in the ocean carbon budget is the logistical difficulty of obtaining time series of conventional ocean observations over the entire globe which make it impossible to rely on surface observations alone for detecting change and understanding processes involved in the exchange of CO_2 between the oceans and atmosphere. Satellite-based observations are capable of filling this gap. In the plan for developing new observations, we stress the need for 1) continuing and improving estimates of productivity, 2) an expanded emphasis on coastal ocean processes and specific regions of critical importance, 3) development of new remote sensing measurements for important but as yet unobservable variables, and with the overall goal of 4) linking ocean carbon cycle processes to climate variability.

Carbon fluxes into the ocean include air-sea exchanges and terrigenous sources (DOC and DIC) with estimates of the net influx from each being similar in magnitude. Contributing observations to the air-sea CO_2 flux include the surface winds (SSW), SST, sea surface height (SSH), and biological productivity. While sea surface salinity (SSS) observations would also be useful and has been proposed under the ESSP, our plans are to have it be obtained through data assimilation and modeling until reliable observations are available. While global satellite observations of SSW, SST, and SSH are well-established, those for ocean productivity, DOC and DIC are not. Without the biological uptake of CO_2, large areas of the ocean (e.g., the North Pacific) would be CO_2 sources rather than sinks. Without reliable estimates of the magnitude and fate of terrigenous DOC and DIC influx to the ocean, the terrestrial carbon budget accounting is incomplete.

Improved estimates of productivity

The estimation of productivity in the ocean likewise requires, in addition to ocean color, surface winds, SSH, SST, mixed layer depth (MLD), aerosol input into the ocean, and surface solar irradiance. Fluorescence emanating out of the ocean, an indicator of nutritional condition of

the phytoplankton, will be very useful for constraining productivity estimates in a variety of ocean habitats, since current productivity models do not take the plant physiology into account. Fluorescence bands are now available on MODIS, but there are no plans beyond MODIS for a fluorescence observational capability. This is a critical gap in the current program.

MLD is a critical observation for productivity because it influences the light exposure of marine plants, and requires improved modeling capabilities in the absence of detailed observations. Aeolian dust is the primary source of trace nutrients such as iron to the open ocean and satellite observations of aerosol properties are needed to determine the patterns and amounts of dust deposition. Absorbing aerosols such as dust also degrade the accuracy of ocean color products because they absorb light in the same parts of the visible spectrum as phytoplankton. Sensors such as SeaWiFS cannot reliably detect dust contamination, especially at modest concentrations.

Primary production is also a key determinant to the export of carbon to storage in the deep ocean. In addition, however, recent research indicates that the carbon export depends on what organisms are present, i.e., some species generate particles that sink much more rapidly than others do. Also, some species fix nitrogen and thereby enhance primary production in areas that might otherwise be nutrient-limited. In both cases, some key phytoplankton species have unique reflectance characteristics that allow their detection from space. Our strategy for obtaining global primary production data will be to extend the SeaWiFS mission and merge the SeaWiFS data with MODIS data products (data merger is an aspect of the SIMBIOS program). The combined observations provide a substantial increase in coverage over a single mission primarily because the MODIS and SeaWiFS missions are at different times of day which minimizes data loss from cloud cover and also because SeaWiFS tilts to avoid sunglint, thus providing better coverage of the tropical oceans. Data merger will also allow the fluorescence data from MODIS to be used to improve the primary production estimates derived from SeaWiFS. In the latter phase of the GCCP (the second five years), an Ocean Carbon Mission (OCM) is proposed to complement NPP/VIIRS, after the SeaWiFS and MODIS missions end. The specific advantages of the OCM are outlined below.

Coastal areas and regional studies

For coastal areas, we plan to augment coarse resolution data from the OCM and VIIRS instruments with high resolution, but infrequent coverage, of the nearshore and estuarine areas as part of a low-biomass terrestrial mission. This would be contingent on the measurement approach selected for low-biomass terrestrial measurements being an appropriate passive optical system compatible with the coastal ocean measurement requirements.

Our program necessarily incorporates in situ observations to establish the underlying processes, which lead to distributions and variability seen from space. We also expect partners in other agencies (particularly NOAA and NSF) to participate in validation of satellite data, and to make complementary in situ observations; for example, direct air-sea CO_2 flux measurements, and deep-sea observations from ships. While the focus of the program is global, certain areas are indicated to have larger climatic signals (e.g., the Southern Ocean), or else have greater societal impact (e.g., coastal regions). Shipboard programs will be concentrated in these areas for more efficient scientific progress.

The pool of DOC in the ocean is one of the largest carbon reservoirs in the active climate system. Terrestrial export of DOC to the coastal ocean is thought to be a significant fraction of the net terrestrial carbon fixation. The exact amount and the fate of this carbon has not been

established with any certainty. In coastal regions, remote sensing can assist in determining the amount of DOC using algorithms based on DOC absorption in the UV portion of the spectrum. Also, the dynamics of DOC in the open ocean maybe become more important under certain climate change scenarios. Observations in the UV for DOC algorithms are required, but are not available from SeaWiFS, MODIS, or VIIRS.

Linking the ocean carbon cycle to climate variability

The observation plan to link the ocean carbon cycle with climate variability is summarized below and includes the OCM which is characterized by the following:

1) Continued systematic observations of ocean color (for productivity) using MODIS and an extended SeaWiFS data buy;
2) Fluorescence observations for improved productivity estimation;
3) Ocean reflectance observations that allow identification of organisms contributing to the carbon flux to the deep sea and nitrogen fixation;
4) Unambiguous dust detection capabilities (possibly absorbing aerosol concentrations);
5) Enhanced ocean reflectance observations that allow estimation of particulate and dissolved organic matter concentrations, particularly in coastal waters.

These new ocean carbon measurements will augment NPP and NPOESS/VIIRS in a number of ways. Data merger techniques will be developed that allow ocean carbon observations (e.g., dust detection flags and patterns of fluorescence) to be applied to VIIRS data, thereby increasing the utility of the VIIRS data.

Instrument concepts

For these new measurements of primary production, POC, and DOC, aircraft-mounted instruments will be needed (some already exist, e.g., a low altitude combination hyperspectral radiometer-dual pulse lidar system) to support technology development, algorithm development, and field studies such as the NACP. In addition, other shipboard and aircraft measurements for other important properties, e.g. ocean particle profiles, the mixed layer depth and ocean bicarbonate concentrations, will be developed and used in support of the field studies, even though satellite versions are not feasible within the time frame of the GCCP. Ocean particle profile and MLD measurements are under development for shipboard deployment and is based on a lidar system to profile particle backscatter, but signal detection and laser power limitations make space applications infeasible for the near future. These measurements may eventually be possible from space as technology advances and the development of ground-based systems lay the foundations for future measurements beyond the present plan.

A3.4 Model Development Requirements

Among the primary efforts of the GCCP will be numerical modeling of relevant processes involved in the global carbon cycle, model data assimilation, and observing system simulation experiments. Data assimilation and OSSEs were discussed in Section 2.2 and the need for these will not be reiterated here. All these model related developments need to be accelerated.

Coupled models are defined as those that combine processes from 2 or more disciplines or sub-disciplines. Disciplines are the general fields of atmospheric, oceanic, and terrestrial sciences. The purposes of these coupled models are:

1) Develop a platform for understanding how processes and outputs relate to remote sensing in order to define feasibility
2) Provide realistic Earth system data sets for observing system simulation experiments, where sampling and measurement options can be evaluated, along with mission feasibility.
3) Further understanding of the interactions among interacting processes using remote sensing data as a validation tool
4) Serve as an interpolation/extrapolation capability in the process of remote sensing data assimilation to extend the observational capability of remote sensing in 3-dimensions
5) Provide, through the assimilation of remotely-sensed data, long-term monitoring of the state and trends in carbon cycle processes
6) Provide forecast capability for future carbon cycle trends

Disciplinary models

Disciplinary models combine processes from 2 or more sub-disciplines. In the case of the GCCP, these models range from development and use of coupled physical/biogeochemical models of the oceans, to coupled hydrological/biological models in terrestrial systems, to coupled dynamical/chemical models in the atmosphere. These models can provide a more detailed representation of processes than interdisciplinary models because they are more limited in scope. However, they cannot predict the range of feedbacks feasible with interdisciplinary models.

Interdisciplinary models

Coupled land biogeochemical models to atmospheric circulation models. Models of global land primary productivity are fairly mature. The SiB2, a terrestrial vegetation model, is one such model that is coupled to atmospheric GCMs and is parameterized from satellite measurements of global vegetation. However, primary productivity is only half the story for the atmospheric CO_2 budget, the other half depending on biospheric respiration and decomposition. Current generation respiration/decomposition models will be implemented in the climate models for long term climate prediction and numerical weather prediction models for seasonal/interannual forecasts of CO_2 fluxes. The new models will be developed to exploit new types of satellite data as boundary conditions and for validation.

Coupled ocean biogeochemical models with ocean circulation models. Coupled ocean models integrate physical and biogeochemical processes to produce a dynamical representation of phytoplankton and nutrient distributions and can include carbon chemistry. These models rely heavily on improved understanding of fundamental processes describing each model component (e.g., phytoplankton photosynthetic parameterizations, general ocean circulation fields, radiative fields, and loss terms) and on satellite data for constraint of output fields. Coupled models function as the basis for understanding complex interactions between processes involved in the carbon cycle and provide the greatest forecasting potential, especially when coupled to improved process-oriented variable parameterizations. Expansion of capabilities to further complement national goals in coupled modeling requires adaptation to carbon-specific outputs, incorporation of new carbon pathways, and better utilization of satellite data. A particularly new thrust is the

extension of present models to the dissolved inorganic carbon cycle, i.e., the calculation of CO_2 update for carbon fixation and return via respiration. Also required is the coupling of existing coupled oceanic models with atmospheric circulation models and land process models.

Global atmospheric chemical transport modeling. The numerical simulation of CO_2 transport (and other tracers such as N_2O, CH_4, and biomass burning tracers) in the atmosphere is required to determine the fate of anthropogenic source gases. The exchange of CO_2 between the surface ocean, terrestrial biosphere and the atmosphere is of first order importance in understanding the global carbon cycle and those processes that are most important in determining the atmospheric concentration of CO_2. The global 3-D atmospheric modeling of CO_2 provides the basic framework to analyze existing and proposed measurement network data and satellite remote sensing of CO_2 distributions. Global 3-D chemistry and transport studies will be used to simulate atmospheric CO_2 and other constituents. The model will include surface fluxes provided by land and ocean components.

Atmospheric modeling of the transport of mineral dust iron. The deposition of iron in mineral dust aerosol to the oceans has been suggested to be very important in controlling the biological activity that plays an important role in the oceanic carbon abundance. Ocean biological productivity, and hence CO_2 uptake, may be limited by iron availability. Since the main source of iron to most oceanic regions is atmospheric mineral dust, the 3-D modeling of dust concentrations and deposition is critical to the oceanic carbon cycle analysis. Present studies are using a global 3-D chemical transport model to compute dust transport and deposition to the world ocean. This modeling is closely tied to absorbing aerosol measurements from the TOMS satellite instrument. These dust fluxes are critical to the biological modeling work discussed under the ocean effort.

Global air-sea CO_2 fluxes computed using meteorological data assimilation products. Computation of the surface exchange coefficients for CO_2 is a critical aspect of modeling the carbon cycle. The air-sea exchange of CO_2 and other tracers can be calculated given surface ocean/lower atmosphere concentration gradients and estimates of the transfer velocity. The NASA DAO models have good quality, highly resolved global meteorological fields, including wind speed, in the lower troposphere. These may be used to improve transfer velocity distributions and hence CO_2 flux calculations globally. They could also be used to model the trace gas fluxes for those locations and times that actual measurements are being made during a field campaign. The use of new surface roughness estimates from satellite (in collaboration with the ocean effort discussed above) will be compared to transfer velocity estimates and fluxes derived from assimilation data products.

Simulations of past, present and future climate for input to carbon cycle models. The physical climate system strongly influences the surface exchange of CO_2 in several ways. In the terrestrial biosphere, precipitation, wind stress, surface radiation, boundary layer properties, temperature, soil moisture and other variables all influence the flux of moisture and chemicals between the Earth's surface and the atmosphere. The current general circulation modeling effort includes a highly sophisticated physical representation of atmospheric processes. Computed climate variations can be used as input to carbon cycle process models to examine potential feedbacks between the climate system and surface carbon exchange. This includes paleoclimate

models and simulation and 10-100 year future climate simulations. The ultimate objective would be a coupled carbon-climate model linking modules developed from other areas.

Interactive vegetation-climate modeling on interannual to interdecadal time scales. Climate change and variability strongly impact both the biophysical and biogeochemical aspects of vegetation. The fate of anthropogenic carbon is strongly influenced in turn by the terrestrial biosphere. The emerging coupled atmosphere-ocean-land-vegetation models are expected to provide a comprehensive understanding of these processes and improve the prediction of future trends in atmospheric CO_2 concentrations. Recent efforts have shown the tight coupling between the atmosphere and dynamic vegetation processes on interdecadal and interannual time scales. Research is presently being conducted to improve interannual climate and ecological prediction in tropical regions using coupled vegetation-climate models. The ultimate goal is to understand the future trend of atmospheric CO_2 and climate within the context of global warming.

Combined atmospheric, terrestrial, and oceanic models to evaluate the effects of human activities and natural variability on the global carbon cycling and climate. There are fewer large scale modeling efforts that utilize all three of the major Earth science disciplines. One of the major goals of this plan is to unite efforts to construct models representing multiple aspects of the global carbon cycle, emphasizing the interdisciplinary nature of the problem, and emphasizing coupling among these disciplines. The overall goal may be several models, but the unifying theme is to understand and predict global carbon dynamics on seasonal to interannual to decadal to century time scales, with models linked to remote sensing data.

To this objective, we intend to develop and link with efforts to produce enhanced representations of the global biosphere and the carbon cycle. On seasonal-to-interdecadal time scales, we will couple OGCMs with ocean biogeochemical/optical models (OBOM), eventually coupling with coupled atmosphere/ocean models. Land surface hydrological models will be enhanced with the carbon components from terrestrial ecological models and coupled with the atmospheric AGCM's. On decadal to climate change time scales, we will link the terrestrial ecological models and OBOM/OGCM's to the climate models of the Earth system. This sequence of coupled models linked to satellite data fields will require substantial development time, but we can envision a satellite system assimilation forecast model that can evaluate and predict changes in anthropogenic forcing of carbon related processes with near-term changes in carbon cycling, which may have important effects on climate and weather systems. In the long term, the processes more fully understood by the coupling of these models will enable improvement of predictions of future atmospheric carbon loading and the consequences. This approach of coupled interdisciplinary models with satellite data in assimilation/forecast mode as well as historical reconstructive mode will provide a fuller understanding of the global carbon cycle, the processes affecting it, and the implications of changes.

A3.5 Computational Support Requirements

As a benchmark for assessing computing requirements, current simulations of a coupled ocean biogeochemcal model containing 7 components with an OGCM require about 3 times the computing power of the NSIPP OGCM alone. Extension of the model to explicitly derive organic carbon (both particulate and dissolved), and adaptation to dissolved inorganic carbon pathways will require extra computing power of about a factor of 10. Since it can require time to adapt and extend the models, especially on global scales, this means that supercomputing

capabilities of about half those demanded by NSIPP are required to meet the medium-term carbon cycle modeling objectives of the GCCP. Future coupling among land, atmosphere and ocean biogeochemical models will scale up computing requirements by an additional factor of 3 in the long term (>3 years). These computational requirements must be dedicated to use by personnel working on carbon-related scientific problems. Funding estimates must include software support and assistance with transitioning to new computational platforms. Oversight and administration of the supercomputer will be performed by the NASA Center for Computational Sciences (NCCS).

The global carbon cycle is diverse and complex. Plant and animal life forms respond differently and have different carbon cycling rates and mechanisms. At present, most models use only a few simplified categories, which creates simulation error. There are also abiotic pathways and storage (bicarbonate in the oceans, soils on land, etc.) that contain their own dynamics, most of which are not presently incorporated into models or only crudely.

Limited computing capacity introduces several types of model errors and limitations including:

1) Insufficient model spatial/temporal resolution, resulting in incomplete representation of fundamental processes

Ocean models often cannot sustain life in the open ocean where nutrients are poor, and have to resort to numerical specification to prevent extinction. New results suggest the importance of mesoscale (10-100 km) processes in providing nutrients to the upper ocean. Present global models are all synoptic scale (100-1000 km), which do not resolve these processes. In addition, finer scale grids are necessary to represent major ocean features, such as the Gulf Stream.

On land, fine temporal resolution is required to understand changes in seasonal cycles, and better spatial resolution is necessary to match the scales occurring in nature.

2) Inadequate coupling among the major components, reducing our ability to understand interactions and their consequences

The relationships among land, oceans, and atmospheres are only minimally understood and poor representations may be the source of the present inadequacies in climate models. A complete simulation may well be beyond our scientific and computing capabilities until well into the future, we must begin to address these issues in the near and medium term. Inadequate computing resources will hinder the development of modeling of these interactions, with lost potential that cannot be quantified at present.

3) Inadequate run-time to evaluate carbon-climate interactions

Carbon cycling is most important because of its potential impacts on climate. These interactions occur at very long time scales (decades to geologic). Unless prevalent computing resources are available, carbon cycle simulations may have to be constrained to shorter time scales and simplistic models.

APPENDIX 4. GCCP MISSION CONCEPT STUDIES

In describing a new measurement, it is necessary to consider the measurement type, rationale and performance drivers, spatial resolution and extent, geographic location, temporal

resolution and duration, timing, special events, repeat cycle, precision and accuracy, ancillary measurements, algorithms, processing, radiative transfer theory, as well as coordination and linkages with field campaigns, aircraft underflights and other satellites. The careful evaluation of these factors leads to a preliminary instrument concept, which describes the type of sensor that might be able to provide the measurement.

The instrument and data system characteristics need to be defined, such as mechanical (mass, volume and fields-of-view), electrical, thermal, calibration, polarization sensitivity, contamination sensitivity, pointing, signal-to-noise ratio, digitization, and on-board data storage and processing schemes, in order to develop a reliable approach for planning and costing. More than one concept might work, but there may be moderate to severe challenges in making any one or all of these concepts work. Furthermore, the more difficult concepts may provide the best performance.

Next the requirements for the mission as a whole, as required by the measurement, must be included to select the appropriate accommodation (spacecraft and launch vehicle) and to ensure that the measurement provides the information needed. These factors include the timeline (coordination, availability, technology development), orbit, operations, ground-to-spacecraft interaction, reliability/performance assurance, guidance, navigation, attitude control systems (ACS), integration and test, and integration, verification, and validation. A final consideration is the actual process needed to design and build a space mission. The process of guiding a mission through all the appropriate stages is laid out in great detail in the NASA program guideline 700-PG-7120.5A.

A4.1 Measurement Requirements

As part of the preparation for the second workshop (March 20-22, 2001), the measurements identified in the first workshop were linked with potential missions. These missions were developed in greater detail and were paired with appropriate spacecraft and launch vehicles in the Integrated Mission Design Center (IMDC) at GSFC. This process examined the various subsystems as well and sought to identify any technology challenges by subsystem and for the mission as a whole. The results of these studies could then be used as a basis for costing potential missions with the assistance of the Resource Analysis Office (RAO) in preparation for the third workshop (May 2-4, 2001). This information could then serve as the basis for an informed prioritization of the candidate science activities, both individually and in synergistic combinations.

Aircraft versions of some of the proposed missions will be needed to understand the measurement characteristics so that the spaceborne instrument can be optimally designed and also to test the instrument design for the space mission. Such instruments will be able to support calibration/validation and field campaigns as well. These aircraft models, and possibly laboratory/bench models as well, will need to be included and costed in the overall plan.

In addition, technology issues affecting multiple space missions were identified with help from the working group and were reviewed with the Earth Science Technology Office (ESTO). This information was be used in the preparation of technology roadmaps designed to solve potential problems and reduce risk for the space missions. These roadmaps were presented at the third workshop. Improvements may also be needed in aircraft, laboratory, and in situ measurement equipment in order to support the remote sensing activities. Technology needed to achieve these improvements was examined and costed for the third workshop.

The duration of the space measurements/missions discussed below is at least three years, technology permitting, in order to acquire information over more than one year. This will generally counteract the effect of a single unusual year by balancing it with two presumably normal years. Orbits are assumed to be standard low-earth orbits, generally sun-synchronous to remove the effects of diurnal variation in illumination and sun angle.

The timeline for development of missions to acquire the selected new measurements is presented in the Mission/Technology Roadmap (Figure 17). The reference mission concept studies, which are described in greater detail in Section 3.3, resulted in a baseline reference mission set, which is reflected in the timeline shown in this figure. Measurements from existing missions which are crucial to the carbon cycle work and from planned missions which represent critical dependencies are also shown on the timeline. Key technology and aircraft/field campaigns needed to support the spaceborne measurements are also highlighted.

The specific activities needed to build and fly these missions, acquire the desired measurements, and produce accurate, useful deliverables to the scientific community and government policy-makers are outlined over time in Section 3.4. These activities will produce near-term (2003-2007) products, intended to assist policy-makers in a timely manner, and long-term (2008-2012) strategies, which will yield long-term solutions to the science questions by revealing the deeper workings of the carbon-climate cycle.

A4.2. Mission Concept Study Methodology

The process followed in developing and costing potential space and aircraft mission concepts and their supporting technology was developed as the science community clarified their questions and developed measurement objectives in the first and second workshops, resulting in a set of measurement requirements. The characteristics of these measurements (e.g., precision, spatial resolution, ground coverage, temporal frequency) were considered in detail to derive potential sensors, spacecraft, and other mission parameters (e.g., orbits), which might be used to acquire these measurements. Past space missions and aircraft missions were used as guidelines (benchmarking). The concept was then further developed by specific engineering studies in Goddard's Instrument Synthesis and Analysis Laboratory (ISAL) and Integrated Mission Design Center (IMDC), which will be described in greater detail in following sections. The output of these studies allowed the selection of possible spacecraft from the Rapid Spacecraft Development Office's (RSDO) catalog and the assignment of probable launch vehicles from the Access to Space (ATS) inventory. Armed with this information and working with the RAO, RSDO, ATS and the Network Services Division, costs were developed for these representative space missions. These findings were in turn discussed with the Science Team at the workshops, culminating in a full presentation of representative mission concepts and costs at the third workshop.

A series of potential missions were studied and refined in the IMDC. These included an Aerosols Polarimeter (December 11-14, 2000), Advanced Atmospheric CO_2 (January 15-18, 2001), High Density Biomass Lidar (January 29-February 1, 2001), and Pathfinder Atmospheric CO_2 (April 2001). A detailed description of the IMDC and the services it provides can be found on their website under www.imdc.gsfc.nasa.gov. Some of the results of these studies will be included with the description of each representative mission below. The ability to examine possible missions, particularly the accommodation of instruments on spacecraft and launch vehicles and their performance in orbit; to clarify their characteristics, identify probable weight,

power, data rates and volume; and to understand potential risks and the needs for technology development in order to reduce those risks is a major goal in mission formulation.

The Ocean Particulate Lidar (previously called the Mixed Layer Lidar) was examined in the ISAL as an aircraft instrument and possible precursor to a space-based mission. This allowed the design of the instrument to be developed in much greater detail and technological advances that would need to be funded for the aircraft and possible space-borne versions of this instrument to be identified. The results are presented as part of the discussion of the aircraft mission below. For more details about the ISAL please refer to their website at www.isal.gsfc.nasa.gov.

A5.3 Technology Requirements

The GCCP plans to utilize a number of active and passive sensor types to meet its ground, air, and space-based observational requirements. Experience to date with new flight systems indicates that technology readiness is a critical ingredient for program success. In order to minimize the risk associated with such systems, the GCCP study team has identified technology pathways for key instrumentation and has outlined a risk mitigation strategy to increase the probability of achieving scientific goals and objectives within cost and schedule guidelines.

The GCCP program intends to leverage existing technology programs like SBIR, ATIP, IIP, NMP and ESSP, wherever possible. It is also seeking focused technology development augmentations to ensure that critical instrumentation moves without interruption up the technology readiness chain. As part of the technology needs identification process, a mission/technology subgroup worked closely with atmosphere, ocean, and land working groups and performed benchmarking studies to highlight the most significant sensor development challenges. An assessment of specific atmosphere, ocean, and land sensor technology needs is given in the paragraphs that follow.

Atmospheric CO_2 technology requirements

A number of passive techniques for CO_2 column measurements were identified and were categorized broadly as either optical or thermal in nature. Some technology development is needed to improve signal to noise ratios and quantum efficiencies for photodiode arrays and mercury/cadmium/telluride detectors. In addition, larger detector arrays, if available, would substantially improve data return from space. Algorithms for combined CO_2/O_2 retrieval in a cloudy, aerosol-laden atmosphere and algorithms that accurately account for effects of varying pressure and temperature, surface reflectance, and other absorbers are additional development challenges.

Three active techniques for CO_2 profiling were also identified, one of which was the subject of a concept study in the GSFC IMDC and the other two in development by teams at LaRC and JPL. The GSFC approach utilizes a two-channel laser sounder in the 1570 nm band for carbon dioxide and the 770 nm band for oxygen. Lidar sensor development is a key technology and is already benefiting from some advanced technology funding via the ATIP program. The challenge is developing a CO_2 and O_2 lidar sensor with the required precision, stability, and lifetime for a space mission. Because of projected power demands, the thermal control and heat rejection system will require careful consideration, although at the component level space qualified thermal control devices already exist. The LaRC Differential Absorption Lidar or DIAL approach to CO_2 global profiling employs a multiple DIAL pair technique and requires high-energy tunable laser transmitter technology development along with a large

deployable receiver telescope. Infrared detector technology development is also critical to the success of space-based DIAL CO_2 measurements. Like the DIAL system described above, the JPL coherent laser absorption spectrometer operates at a frequency of about 2 microns and has similar technology needs. This system, however, is less resource intensive and also has the potential to work in concert with the GSFC laser sounder.

Prior to implementation of a flight hardware build, particularly for active sensors, laboratory measurement demonstration, horizontal path demonstration, and aircraft measurements with a representative version of the proposed instrument will be made to compare with measurements from in-situ sensors. In addition to their science calibration/validation function, these mission precursors will assist in the design process for the eventual space flight instrument.

Ocean carbon technology requirements

Several measurements of importance to ocean working group representatives require active sensors. A lidar technique has been proposed to measure ocean bicarbonate, the major component of dissolved inorganic carbon. A study was also performed in the GSFC ISAL to develop an initial concept for a 532 and 1064 nm lidar that would measure particulates within the upper mixed layer of the oceans. Finally, an active fluorescence experiment using a pump and probe lidar with sources at 532 nm and 355 nm and detector at 685 nm has been demonstrated to measure photosynthetic parameters related to chlorophyll and biological productivity. Relative to the immediate goals and objectives of the GCCP, these observations are currently scoped as a series of aircraft flights. Improvements in spaceborne lidar technology are needed to fully utilize these as spaceborne sensors.

The ongoing SeaWiFS program and planned observations of passive fluorescence from MODIS are being used to study organic carbon in the open ocean. These types of observations need to be extended beyond the lifetime of these existing sensors. Furthermore, there is a renewed emphasis on coastal studies for tracking the movement of carbon between the land or rivers and the sea. These studies should be performed in the ultraviolet, visible, and near infrared using an instrument with a spatial resolution similar to MODIS (250 m or less) and a band selection tailored to sensing dissolved and particulate organic carbon, particularly in the near-shore environment. Such an instrument would initially fly on an aircraft, but would ultimately be developed for the proposed ocean carbon space mission. The enhanced SeaWiFS type instrument would include bands for improved ocean productivity measurements (typically 660 and 680 nm) and bands in the ultraviolet for dissolved organic carbon. The technological challenges include selection of bands not generally used in land applications, improvements in sensor design, and the use of onboard data processing to optimize data retrieval. As with SeaWiFs, the spacecraft and instrument should accommodate routine lunar and solar calibrations.

In-situ instruments are particularly important for the planned GCCP measurement and instrument development activities and for the field campaigns and calibration/validation efforts that follow. Specific technologies are sought that improve the precision, accuracy, range, and reliability of ground-based measurements and of the aircraft and space missions they support. The miniaturization of drifter buoys with optical, pCO_2, and nutrient sensors is one such improvement that has already been identified.

Biomass observation technology requirements

The land working group identified a technology wedge that would enable new or improved measurements of biomass, biomass change, ecosystem disturbance, disturbance recovery, and primary productivity. A timetable was proposed that exploited existing or planned space assets, such as Landsat, SeaWiFS, EOS/Terra, and VCL, and allowed for development of new observational capabilities. In the near term, improved land cover algorithms that are more automated and merge data from multiple sensors are sought to extend observational capability over more biomes, disturbance types, and biomass ranges. Changes in biomass occur over a wide range of temporal and spatial scales and include responses to and recovery from disturbances and climate signals. Disturbances include both very rapid processes, such as fire and catastrophic storms, and more incremental changes from causes such as land use intensification, acid deposition, pests and pathogens, and human suppression of fire. As part of the proposed GCCP, space-based observations are therefore needed that embrace the full range of biomes so that global carbon assessments can be made.

Technologies supporting identification of land cover itself are relatively mature. Moderate resolution, multispectral, passive optical sensors permit fine resolution mapping of land cover parameters, whereas coarse resolution, passive optical sensors allow the creation of dense spectral time series. However, further progress in determining global biomass and biomass change requires direct measurement of three-dimensional vegetation structures using other measurement techniques. In this regard, both broad-band and hyperspectral passive optical sensors, radar, active lasers/lidars, and bi-directional reflectance type instruments are worthy of further study. Hyperspectral measurements offer improved discrimination of land cover type, especially for low biomass systems. Synthetic aperture radar (SAR), on the other hand, enables repeated observations of boreal and tropical ecosystems over which acquisition of optical imagery is often precluded by cloud cover or darkness. For their part, lidars provide height or surface roughness images from which the magnitude of carbon stocks can be deduced, particularly for high biomass systems. A sensor fusion algorithm development effort is also needed to combine height information from VCL with existing land cover sensor data from Enhanced Thematic Mapper (ETM+), MODIS, and MISR to produce vegetation biomass and biomass change maps.

Specific technology needs have been identified for each of the above referenced sensor types and are described here. Hyperspectral imagers, potentially useful for low density biomass/coastal ocean carbon cycle measurements, will require much higher signal to noise ratios than those achieved for the EO-1 Hyperion instrument. In addition, large area focal plane arrays, large capacity onboard data recorders, and high rate downlink communications systems are needed to improve mission performance for a system with data rates approaching 700 Mbps. There is also a stated need for the development of an in-situ imaging hyperspectral spectrometer for algorithm development and validation of aircraft and spaceborne instruments. A high resolution P-band polarimetric SAR, consisting of a deployable antenna and an electronics module, is another proposed instrument that can make high density biomass measurements in concert with a single or dual frequency lidar. These lidars, more capable than the MBLA on VCL, require a significant technology investment to develop pixelated detectors for terrestrial biomass imaging. Detector options include conventional avalanche photodiodes, photon counting, or optical lens arrays. In addition to woody biomass (trees and shrubs), images could also be made of herbaceous biomass (grasslands) by adding a red channel to the single frequency lidar and shifting its near infrared channel to a shorter wavelength. The key technology for this

dual frequency lidar is the selection and development of the optimal technique to provide a red channel between 650 and 680 nm. Candidates include frequency mixing, crystal doubling, and Raman shifting. Biomass lidars also rely on a high accuracy attitude and position knowledge package for precise geolocation measurements that provide the required 1 to 2 arcsec post-processed attitude knowledge. Options for this ACS related hardware include a dual frequency global positioning system (GPS) with carrier phases on both frequencies along with a star tracker and a stable gyro, or an integrated attitude and position knowledge package. Finally, more advanced multi-angle and polarization type instrument simulators of MISR heritage need to be demonstrated via aircraft flights. Data from these flights must then be compared with in-situ calibration/validation measurements to assess performance.

Laser technology readiness

As proposed, the GCCP will utilize a significant number of lasers to meet its aircraft and space-based observational requirements. In particular, laser and lidar systems are envisioned that perform biomass imaging, atmospheric carbon dioxide profiling, and ocean carbon measurements. Recent difficulties with several laser/lidar missions under development have heightened awareness of the importance of technology readiness and comprehensive testing. A report from the Earth Science Independent Laser Review Panel summarizes key issues and recommendations.

In order to adequately assess the risk associated with active sensors under consideration for the baseline carbon cycle mission set, a laser/lidar benchmarking study was performed. This study compared key GCCP instrument design and performance parameters with those from previous or planned missions such as Shuttle Laser Altimeter (SLA), Lidar In-space Technology Experiment (LITE), Space Readiness Coherent Laser Experiment (SPARCLE), Geoscience Laser Altimeter System (GLAS), VCL, and Picasso-Cena. Instrument parameters included lifetime, orbit altitude, laser type, telescope size, mass, power, data rate, spot size, energy, wavelength, pulse length, pulse repetition frequency, and number of shots. It was concluded that, although there was clear heritage in many cases, GCCP requirements exceeded those of previous instruments in at least several of its key design or performance parameters.

In a further attempt to identify the state of technology readiness for some candidate laser/lidar systems, a detailed decomposition or component by component evaluation was made for single and dual frequency biomass imagers and for an atmospheric CO_2 laser sounder and differential absorption lidar. These assessments highlight instrument components and subsystems in need of advancement. In addition to the above specific laser/lidar instrument technologies, there is a set of generic or common elements that need attention. These include improvements in laser diode reliability and efficiency, development of better materials and coating damage test techniques, enhancements to performance modeling, and qualification of commercial fiber lasers and amplifiers for space-based remote sensing. A questionnaire was also prepared and distributed to select atmosphere, ocean, and land science team members in order to collect related technology needs for aircraft and in-situ measurements of importance to carbon cycle calibration/validation activities. Both new equipment and improvements to existing instrumentation were solicited.

Laser risk mitigation

As a result of the referenced benchmarking studies and several laser review panel recommendations, a cursory risk mitigation strategy was developed at the program, mission, and

instrument level for observations employing both active and passive sensors. At the program level, an architecture has been developed that includes the technology and instrument investments needed to enable the desired measurements. The technology development funding requested is significant and is detailed in the cost section of the GCCP. Alternate technology paths will also be pursued wherever feasible, and technology needs for missions beyond the proof-of-concept will be supported. Technology readiness will ultimately determine the order of the core flight missions. At the mission level, substantial mass and power margins will be maintained for new active and passive instrument systems and adequate redundancy will be incorporated into all mission critical flight systems. Moreover, comprehensive testing at the system level before acceptance for flight is viewed as a critical performance assurance element and will be allotted appropriate financial and schedule resources. Finally, a number of steps will be taken to reduce risk at the instrument level. These include the following:

1) A technology readiness level of 6 is proposed before the instrument implementation phase can begin;
2) An engineering test unit is included as part of the flight instrument development program for active sensors;
3) Life testing will be performed on all critical mechanisms and laser system components;
4) Existing technology programs will be leveraged to the fullest extent possible.

Carbon cycle mission concept studies, described next, indicate that the present list of candidate spacecraft can accommodate the instruments and observations described in the previous paragraphs with minor modifications. Existing launch vehicles and ground systems, though not optimal, are also adequate for all requirements, but the balance between distributed and centralized data systems needs to be explored. The greatest challenge lies in the development of active and passive sensors, particularly lidars, to perform extended global measurements. A coordinated and well-funded technology program to improve performance and reduce risk is proposed. Careful attention must also be paid to scaling of aircraft instrumentation for space flight. Recent experience demonstrates that this transition imposes some technological hurdles that must be addressed early in the development phase.

A4.4. Mission and Technology Concept Study Results

An initial set of observational goals and requirements were established in the proceedings of several early GCCP workshops. With these as a starting point, the project formulation and systems engineering team began its work to develop a number of space mission candidates that would provide the desired measurements. Rough concepts were first developed and then definition studies were performed. Various sources were employed in this concept generation including related university, industry, and government studies. A broad spectrum of single and combined instrument mission types were evaluated and are listed below:

Single Instrument Missions	Combined Instrument Missions
Atmospheric Aerosols	
Column CO_2	Atmospheric Aerosols and Column CO_2
CO_2 Profiling	CO_2 Column and Profiling
Ocean Carbon	Ocean Carbon and Column CO_2
Single Frequency Biomass Lidar	

Dual Frequency Biomass Lidar	
SAR	Biomass Lidar and SAR
Hyperspectral Imaging	Hyperspectral and SAR

These studies evolved into a representative or baseline set of five space missions endorsed by the science team and described in the paragraphs that follow. Table A4.1 provides a summary of assumed measurement requirements for these studies.

Table A4.1 Assumed measurement requirements

Measurement	Characteristic	Spatial Resolution	Spectral Range	Precision Accuracy	Temporal Frequency	Orbit
Atm. CO_2	Column	10 km	VNIR	1-2 ppmv	Monthly	Daytime
	Profile	100 km, 3 layers	Lidar - NIR		Monthly	Dawn-Dusk
Ocean Carbon	DOC	1 km	UV		Daily	Daytime
	Fluorescence	1 km	NIR		Daily	Daytime
Land Biomass	Low Density	10 m - 250 m	VNIR SWIR		2 weeks	Daytime
	High Density	0.5 m vertical	Lidar, SAR		2 weeks	Dawn-Dusk
Aerosols			Polarimeter			60^{o} Daytime

Note: Sun synchronous (unless otherwise stated), low earth orbits, and mission duration of at least 3 years (technology permitting), assumed.

Pathfinder atmospheric CO_2 mission concept

The consensus of the carbon cycle science team was that a pathfinder mission to make high precision (1 to 2 ppmv) global measurements of atmospheric column CO_2 abundance should be viewed as a top priority. Although a number of different measurement techniques exist, a concept was proposed that used a passive spectrometer with 10 km resolution. High signal-to-noise ratio detection of both CO_2 and O_2 during the daytime portion of the orbit is required. Several small, low-cost, three-axis stabilized, nadir-pointing spacecraft were found in the RSDO catalog that could accommodate the instrument with adequate mass and power margins. A 500 to 700 km polar, sun-synchronous orbit with a late morning crossing time would provide the appropriate altitude and environmental conditions for data collection. A Pegasus XL or equivalent class launch vehicle was deemed adequate for this mission concept. Orbital life was proposed as three years.

Ocean carbon mission concept

Comprehensive observations of the world's oceans in the ultraviolet, visible, and near infrared portions of the electromagnetic spectrum are required for investigations of the marine biosphere, its variability, dynamics, and biogeochemical cycles. Enhancing and continuing the measurements initiated by the Nimbus-7/CZCS, SeaStar/SeaWiFS, and EOS/MODIS instruments are critical in establishing the role played by the oceanic biosphere in the global carbon cycle.

The proposed ocean carbon mission is a small satellite mission that meets the above scientific objectives by making those ocean color measurements required for determination of ocean biomass, primary productivity, and dissolved organic matter. Irradiance measurements in 10 spectral bands from the ultraviolet to the near infrared are made by a rotating, scanning telescope equipped with an on-board solar calibrator. A small, low-cost, three-axis stabilized, nadir-pointing spacecraft provides the platform for the instrument telescope and associated electronics. A propulsion system is employed for orbit raising after launch by a Pegasus XL or equivalent, as well as for orbit maintenance and maneuvers. One such maneuver is a monthly spacecraft rotation essential for lunar calibration of the instrument. A 705 km polar, sun-synchronous orbit with a 12:00 noon crossing time is ideal. For planning purposes, a five-year mission lifetime has been assumed. In-situ measurements from ships and optical buoys provide additional calibration and validation data for comparison with the spaceborne instrumentation.

Low density biomass/coastal ocean mission concept

Satellite observations provide the only practical means to obtain a synoptic view of the Earth's ecosystems along with their spatial distribution and temporal dynamics. Four priority areas have been identified where improved space-based measurements would significantly reduce the uncertainties in the global carbon budget. These include: (1) land cover characterization at higher spatial resolution, (2) above-ground biomass estimates, (3) areal estimates of disturbance and recovery, and (4) improved estimates of terrestrial and coastal ocean productivity.

In order to achieve the scientific objectives outlined above, a concept was developed for a low density biomass/coastal ocean mission that carries an advanced hyperspectral imager with heritage traceable to the Hyperion instrument demonstrated on the Lewis and NMP EO-1 missions. Active systems such as lidars are of limited use over grasslands and sparsely vegetated areas. The proposed instrument has a high signal-to-noise ratio detection system and covers a frequency range from 360 to 2350 nm. The instrument contains a SWIR spectrometer element with a bandwidth of 10 nm and a VNIR spectrometer with a bandwidth of 5 nm. Several candidate low-cost, three-axis stabilized, nadir-pointing spacecraft were identified that met instrument requirements with margin. However, some modification to the standard spacecraft command and data handling (CDH) and communications subsystems is anticipated in order to accommodate the inherently high data rates associated with hyperspectral sensing. A propulsion system was also included in the configuration to allow for orbit maintenance and for possible formation flying with other land imaging platforms. A 705 km sun-synchronous orbit with a 10:30 am descending node was the orbit of choice. A Taurus launch vehicle or equivalent was judged to be adequate for the integrated payload described above. A mission life of five years was chosen in order to provide a period of time sufficient for monitoring biomass change.

High density biomass mission concept

Although a number of discrete space assets for land remote sensing exist, the science team desired a mission that would simultaneously improve regional and global estimates of vegetation biomass and carbon stocks, measure the response of terrestrial ecosystems to major disturbances, and monitor rates of recovery. Disturbances, as defined in this context, include both very rapid processes, such as fires and catastrophic windstorms, and more incremental changes from land-use intensification, acid deposition, and insect infestations.

Because hyperspectral measurements are of limited utility for biomass measurements in forests, an active system was considered. A mission concept was proposed that employed two flight instruments to provide the desired biomass measurements. These included a P-band SAR operating at 0.44 GHz and a multi-track, 1.064 micron, imaging laser altimeter with a capability of resolving 0.5 m differences in vegetation height. A three-axis stabilized, nadir-pointing spacecraft was required to accommodate the referenced instruments. Either a spacecraft from the RSDO catalog with appropriate modifications or another spacecraft with extensive flight heritage could be used. A large propulsion system for orbit maintenance and disposal and an X-band phased array for downlink of science data could be part of the final configuration. A 400 km polar, sun-synchronous orbit with a 6:00 pm ascending node was tentatively selected. Launch of the integrated payload requires a Delta II or equivalent vehicle in order to meet mass and volume expectations with margin. A mission lifetime of three years provides sufficient data to meet measurement objectives.

Advanced atmospheric CO_2 mission concept

Knowledge of global atmospheric CO_2 distribution in the lower troposphere is essential for understanding the carbon cycle and for solving the missing carbon sink mystery. Presently, however, atmospheric CO_2 is very poorly sampled. In order to address this deficiency, a study was performed in the GSFC IMDC to develop an advanced mission concept that measured CO_2 and O_2 column extinction from laser surface echoes. This sounding technique, based on GLAS/ICESAT instrument heritage, uses a pulsed, dual frequency, tunable laser operating in the 1570 nm band for carbon dioxide detection and in the 770 nm band for oxygen detection. A few low-cost, three-axis stabilized, nadir-pointing spacecraft were identified in the RSDO catalog that could meet instrument accommodation requirements with modest modifications, particularly to the power and propulsion subsystems. A 590 km polar, sun-synchronous orbit with either a 7:00 am or 7:00 pm ascending node provided a suitable environment from which to make the desired measurements. Launch to orbit was by means of a Delta 2320-10 or equivalent vehicle. A three-year mission life was considered sufficient to meet science objectives.

Instrument options at a lower level of technology readiness, but with vertical profiling capability, include a coherent laser absorption spectrometer or a differential absorption lidar each operating at a frequency of about 2 microns. Mission studies for these alternatives have been conducted by the JPL and LaRC teams, respectively.

Aerosols mission concept

In response to management direction to more closely link carbon cycle and climate research, a previously studied aerosols mission was added to the set of potential GCCP space observations. The primary objective of this mission is the global characterization of atmospheric aerosols, their spatial and temporal variability, and the corresponding impact on climate.

In this concept, a high-precision photopolarimeter provides multi-angle measurements of reflected and scattered sunlight in nine spectral bands ranging from 0.41 to 2.25 microns. A polarization-compensated scan mirror is also included as part of the instrument for acquiring multiple samples of intensity and linear polarization from one end of the Earth's limb to the other along the spacecraft ground track. A small, low-cost, three-axis stabilized, nadir-pointing spacecraft from the RSDO catalog will readily accommodate the very modest instrument requirements. No propulsion system is needed for orbit maintenance or disposal. A 550 km circular orbit with an inclination angle of 60° was recommended although other orbits could be

considered. The launch vehicle of choice was the Pegasus XL or equivalent. Mission lifetime was specified as two years minimum with a goal of five years.

Finally, it should be noted that a number of mission options exist. These include, in addition to the single dedicated mission outlined above, dual spacecraft in LEO and sun-synchronous orbits or flight of the instrument alone as a payload of opportunity on another Earth viewing spacecraft.

A4.5. Aircraft Instrumentation in Support or Space Misssion Concept and Technology Development

Carbon cycle aircraft instruments are envisioned supporting either carbon cycle space missions or future concepts for measuring the carbon cycle from space. The first is primarily for development of the five space missions endorsed by the carbon cycle science team. The second is to prove future space measurement concepts; as well as, increase field measurement accuracy and coverage. The five carbon cycle space missions will use a tailored mix of new and existing aircraft instruments. A single new aircraft instrument will be developed for each future space measurement concept.

Aircraft instruments will perform four types of air missions: Integration and test flights for each new aircraft instrument, measurement validation of the carbon cycle space instrument or future space measurement concepts, field campaigns, and calibration/validation of carbon cycle space instruments after launch. All new carbon cycle aircraft instruments supporting carbon cycle space missions will be capable of performing all four aircraft missions. However, actual use of each new instrument for field campaigns, and calibration/validation of carbon cycle space instruments after launch will be determined at the time of deployment. These three classes of aircraft missions are described in the science discussions in this document. Only the integration and test flights for each new aircraft instrument will be described in this section.

Only three new aircraft instruments are necessary to support the five space missions endorsed by the carbon cycle science team. The new aircraft instruments supporting the carbon cycle space instruments will be developed between 2002 and 2005. A single new aircraft instrument will be developed for each future spacecraft instrument concept.

Pathfinder CO_2

The Pathfinder CO_2 aircraft instruments will prove the carbon cycle concept for local measurements of tropospheric CO_2, cloud and aerosol properties. At least four passive carbon dioxide instrument concepts will be investigated; however, only two instrument concepts will be competitively selected for development as new aircraft instruments. The Fabry-Perot interferometer (FPI) for column CO_2 married with an A-band spectrometer for column O_2 was chosen as an aircraft instrument representative of the passive carbon dioxide space mission to be used for cost estimation.

The FPI measures CO_2 at a wavelength of 1580 nm. The A-band spectrometer measures O_2 at a wavelength of 760 nm. The integration and test flights for this interferometer and spectrometer combination are planned for the half-meter diameter port on a LearJet. The LearJet was chosen as the lowest cost high altitude aircraft.

Advanced CO_2

The advanced carbon dioxide aircraft instrument will prove the carbon cycle measurement concept for local concentration profiles of CO_2 and O_2 in the lower troposphere.

The carbon dioxide lidar was chosen as the characteristic aircraft instrument representing the advanced carbon dioxide space mission. The carbon dioxide lidar measures CO_2 at the 1580 nm lidar channel and O_2 at the 761 nm lidar channel. The carbon dioxide lidar aircraft instrument was matched to the 1 m^2 port of the P3b. The Wallops Flight Facility P3b provided ports and science crew accommodations of sufficient size to house the carbon dioxide lidar aircraft instrument.

High density biomass

The high density biomass aircraft instrument will estimate local and regional vegetation biomass and carbon stocks; in addition to, measuring structural changes in forests and woodlands. Either a biomass single or dual frequency lidaraircraft instrument was selected as representative of a high density biomass space instrument. The high density biomass aircraft instrument operates at both 1064 nm and 630-680 nm using imaging laser altimeters. The integration and test flights for this lidar will use either the 1m^2 or half-meter diameter port of the WFF P3b. The P3b was primarily chosen for the integration and test flights because of availability, accommodation for the science crew size, and flight duration. A long range business jet similar to the DOE Citation would be a less expensive alternative for field campaigns, and calibration/validation of carbon cycle space instruments after launch. .

Superactive-passive airborne sensor (SAP)

SAP will demonstrate the feasibility of local monitoring of ocean and coastal primary productivity and possibly biomass and taxonomic variability. The measurement will be preformed using a unique combination of short-pulse pump and probe lidars and passive sensors. SAP will be mounted on the one-meter diameter port of the WFF P3b. The P3b port sizes, science crew accommodations, altitude and duration are ideal for the SAP.

Ocean particulate lidar

The ocean particulate lidar aircraft instrument was designed using the ISAL to determine the feasibility of estimating ocean mixed layer depth globally from space by using lidar. The ocean particulate lidar aircraft instrument gauges mixed layer depth by measuring the range-gated 532 nm lidar channel return and the surface roughness by measuring the 1064 nm lidar channel. The ocean particulate lidar aircraft instrument was designed for the WFF P3b 1x4 meter unpressurized forward port. The ocean particulate lidar aircraft instrument was designed by the ISAL to match the P3b port sizes, altitude, duration, and hold the science contingent.

Bicarbonate lidar

Conceptually, the bicarbonate lidar aircraft instrument will remotely measure the bicarbonate ion concentration in seawater. The bicarbonate lidar aircraft instrument measures at the optimum laser wavelength for stimulation of the bicarbonate ion Raman scattering. The WFF P3b one meter diameter port was planned for the integration and test flights for this bicarbonate lidar aircraft instrument. The P3b was planned for the bicarbonate lidar primarily due to the required science crew size, altitude and duration.

Ocean carbon

No aircraft instrument was required to support the Ocean Carbon spacecraft instrument.

Low density biomass/coastal ocean

The low density biomass/coastal ocean aircraft instrument will quantify land cover and ocean surface chlorophyll. Any hyperspectral instrument capable of a 450-2350 nm spectral coverage, such as AVIRIS, or TRWIS III, can perform as the low density biomass/coastal ocean aircraft instrument. The AVIRIS AVARIS aircraft instrument, with 224 contiguous channels, approximately 10 nm wide in the visible to near-infrared (400 to 2500 nm), was chosen as representative of a low density biomass/coastal ocean aircraft instrument. The AVIRIS has flown on an ER-2 but could also be mounted on the AVARIS was planned for the half-meter diameter port of the Twin Otter, which is low in cost and widely available.

High density biomass

The high density biomass aircraft instrument will make local and regional estimates of vegetation biomass and carbon stocks with a measurement of structural changes in forests and woodlands. The largest aircraft instrument suite; the AirSAR with the Laser Vegetation Imaging Sensor (LVIS) was elected as representative of the P-band SAR with profiling LIDAR concept. The P-band SAR radiates at 20 MHz within the continental United States. LVIS lidar measures biomass at the 1064 nm lidar channel. The AirSAR with LVIS will be mounted on the half-meter diameter port and use the external SAR antennae on the Dryden Flight Facility DC8. The integration and test flights for this combination of P-band SAR with profiling lidar are planned for the DC8 because AirSAR was developed for the DC8 which can contain the large instrument and science crew; in addition, the DC8 has the fuselage penetration, high altitude and duration matched to the AirSAR/LVIS combination instrument.

Candidate aircraft were selected for the integration and test flights for each new aircraft instrument. Weight and power requirements did not limit the aircraft choices; however, aircraft selection was primarily limited by port sizes, science crew size, altitude and duration. Therefore, these pertinent specifications are in Table A4.2 for the candidate aircraft.

Table A4.2. Candidate aircraft

Aircraft Name	P3b	DC8	C130Q	Twin Otter	Learjet	Citation	WB57
Operated By	NASA	NASA	NCAR	NASA WFF, NOAA	LaRC	DOE	DOE
Base Location	WFF	Dryden		Various US Sites	Langley, VA	Las Vegas, NV	Las Vegas, NV
Altitude Limit (Kft.)	Up to 30		Up to 26	Up to 17.5	Up to 45	30	30
Duration At Altitude (Hrs.)	Up to 12		Up to 10	5			
Range (Nautical Miles)	Up to 3800		Up to 3800	560			
Speed (Knots)	300		250	160			

Port Sizes	1-150"x27" Unpressurized[1]; 3-36"x27" Pressurized						
Flight Crew Size	7						
Science Crew Size							
Cost Per Flight Hour[2] (Subsidized FY2001)	$3.5K/Flight Hr.						
Crew Cost	Included	Included	Included	Included	300K/ Work Year	TBD	TBD

APPENDIX 5. WORKSHOP SUMMARIES

A5.1. Workshop 1 (January 9 - 11, 2001)

Atmospheres (Workshop 1)

R. Kawa (chair), A. Andrews (rapporteur)

Attendees:	J. Abshire	I. Fung	S. Wofsy
	J. Penner	R. Salawitch	L. Dilling
	C. Barnet	B. Chatfield	D. Wickland
	S. Denning	J. Susskind	J. Gervin
	E. Browell	L. McMillin	C. McClain
	M. Suarez	S. Pawson	J. Bacmeister

Summary of Main Points:

1) The primary objective for the GCCP atmosphere section will be inferring CO_2 surface sources and sinks from atmospheric concentration measurements. The goal will be posed at something like net surface flux accurate to +/- 20% in the annual mean on a spatial scale of 10^7 km^2 with monthly time resolution.
2) Achieving flux objective requires 1) measurement of global distributions of CO_2 and 2) improved atmospheric transport modeling. Goals for these components need to be established. Ancillary measurements, such as CO_2 isotopes, in situ CO_2, and validation campaigns will also be required.
3) Data assimilation will be a major component of model development and data analysis.
4) The chemistry and emissions of CO and CH_4 need to be considered in relation to CO_2 sources, sinks, and distributions.
5) Atmospheric processes must be considered in several important interdisciplinary areas, e.g., air-sea exchange, dust transport and deposition, and water cycle influences on carbon.

Session Report:

The opening discussion concerned the process of defining implementation specifics for the GCCP and the challenge of getting from big generic questions to specifics. It was generally agreed that we should start with the questions from the interagency committee and refine them for NASA focus. It was noted that the interagency goals were too much focused on the North

American sink; that we need to get sinks for all continents. The carbon cycle is global and the magnitude of the N. American sink is only meaningful relative to that for other regions: Eurasian, etc. It was recognized that much of the emphasis on the northern hemisphere was for marketability of the US C Cycle Science Plan. A suggestion was made to put the 3rd bullet (global distribution of sources and sinks and their temporal dynamics) first with the 1st bullet underneath (North American terrestrial carbon sink). The group agreed to move on toward specifics and leave the wording of the big goals to a smaller group at a later time.

A draft set of issues, which would lead toward specific objectives, was presented for discussion. Main issues are 1) inferring fluxes (i.e., surface sources/sinks) from concentration measurements, which leads to major subtopics of atmospheric CO_2 concentration measurements and transport modeling, 2) atmospheric chemistry of CO and CH_4, 3) carbonaceous aerosol processes, and 4) interfaces and cross-disciplinary processes (e.g., dust, soil moisture). First-cut discussion of this list strongly supported CO_2 concentration measurements, transport modeling, and chemistry for inclusion at a high level of visibility. Additional topics that were recommended for top-level focus were isotope analysis to support inferring CO_2 fluxes and atmospheric data assimilation targeted to carbon data and processes. Aerosol processes were seen as very important to climate but it is not clear that they should constitute a major focus for the GCCP. The extent to which they should be pursued in the GCCP may depend on how much climate is in scope.

Interdisciplinary topics were briefly discussed. The hydrological cycle is an important link to the carbon cycle and links to the anticipated H_2O initiative should be solidified. Activities associated with aeolian dust in the GCCP would likely be in the modeling area rather than new measurements, although the Ocean Carbon Mission might accommodate bands for estimating the distribution and concentration of iron in mineral dust aerosols. Also, MISR may have relevant products.

Extended discussion took place on the role of data assimilation. Most see assimilation as central to the GCCP. The view was raised that, based on the NOAA planning implementation exercise, NASA is the only agency in the US that can support assimilation of carbon data for inferring sources and sinks. Assimilation provides an additional step to get from gridded CO_2 observations to surface fluxes. At its crudest level, data provides monthly mean spatial distributions and monthly mean fluxes, but there's potentially much more information in the data. Need to get beyond assimilating concentrations, maybe to assimilating fluxes and even assimilating sources. Goals should be lofty; we are talking about 10 year goals.

Involvement of NASA DAO with the GCCP needs to be motivated. A representative from DAO noted they are swamped with their current tasks and would need more resources to expand their mandate to carbon. DAO is probably best suited for doing atmospheric assimilation while other groups are talking about doing the ocean assimilation and the land assimilation. Some ongoing work at Harvard, Duke, and other places is beginning to explore assimilating CO data and/or fluxes. Assimilation is not just useful for inferring fluxes. May be more generally useful e.g., for filling in spatial distribution from limited measurements. Need to develop techniques. We will need a very sophisticated assimilation system to interpret satellite CO_2 observations, e.g., potential help in dealing with cloud problems and aerosol complications, which will be significant. More discussion on assimilation appears below under the transport modeling topic.

The topic of the role of atmospheric structure, specifically the depth of mixed layer was discussed. Planetary boundary layer (PBL) depth is needed for understanding measurements of

CO_2, particularly from profiling instruments, and for modeling transport of CO_2. Is a lidar measurement of PBL required to improve PBL parameterization in models? May not need ongoing measurement of the PBL, and other methods (e.g., local measurement campaigns and temperature assimilation) may suffice.

PBL depth is one example of a class of problems in atmospheric transport formulation (more below) which also includes cloud-mass flux, convection parameterizations, inversion methodology, and others. Since growth of PBL doesn't change the column (that can be changed only by differential advection or by processes removing CO_2 from column, i.e., surface flux), BL may not be so critical in inferring fluxes of CO_2. An important issue is how CO_2 variations within the PBL and PBL height variations couple into the zonal wind.

Difficulties with inferring fluxes from concentration measurements were discussed. Potential for measurement aliasing must be considered. Diurnal and seasonal flux variations are of opposite sign and comparable magnitude. The turning points for diurnal curve are within an hour of sunrise or sunset so two measurements at these times go a long way toward dealing with diurnal cycle. The diurnal average concentration occurs near midday, but slope is very steep at that time, so one gets a relatively bigger bias. Space-borne sampling is essential for attacking flux problem, but it needs to have a sunrise and sunset strategy. Other issues like clear-sky sampling bias could cause complications for interpretation of CO_2 measurements. We can develop an approach to addressing these problems by looking at tower data. A complementary proposed strategy is to deploy upward-looking spectrometers at many locations to obtain column CO_2 data continuously.

Handling complications due to seasonal bias in CO_2 fluxes may be even more challenging. Data for the monthly CO_2 flux for northeast US shows flux into atmosphere during winter, and out of the atmosphere during summer. Net annual uptake is about 20% of seasonal variation. If we want to measure net uptake to better than 20%, we may need to measure monthly fluxes to ~5%. This is not a constraint on accuracy, only precision. These numbers are based on tower data for the northeast US. Requirements may be different elsewhere. Seasonal variation in PBL height could also be aliased into CO_2 column amounts. Any CO_2 measurement system will need to develop a strategy for dealing with both seasonal and diurnal aliasing.

Discussion then moved to setting quantitative goals for the atmospheric issues. First among these was inferring fluxes. The overall objective for inferring fluxes was stated as the ability to test mechanistic hypotheses regarding surface sources and sinks using carbon mass balances in the atmosphere. Seasonal to interannual variations and spatial distributions over continental-scale regions will be determined and the processes underlying these variations will be characterized.

The required spatial scale for inferring carbon fluxes was agreed to be in the 10^6 to 10^7 km^2 range. This is a higher resolution specification than that used in the current TransCom grid (approximately 25 regions globally), similar to the grid used by Rayner and O'Brien [2001] (8x10°), but less stringent than the IGOS draft (long-term goal of annual fluxes to 15% accuracy over a 10^6 km^2 grid). Regions for determining flux averages are not set by latitude/longitude grid but by biogeophysical domains. These have length scales of about 1000 km over land. This is similar to the length scale for advection acting on the diurnal signal, 10 m/s over 10^5 s. Rayner and O'Brien (2001) find that, for monthly mean averages on an 8x10° grid, column CO_2 must be measured to a precision of 2.5 ppmv to infer carbon sources and sinks as well as can be done using the existing surface network. It was also noted that for a "perfect atmosphere" inversion experiment, similar to Rayner and O'Brien, with CO_2 measurements on a 4x5° resolution grid,

the precision requirement for monthly mean column CO_2 is relaxed to 4 ppmv. The key in these experiments is to reduce the systematic errors in measured CO_2 such as diurnal sampling bias. It was also noted that 10^6 km^2 or better was needed to begin to connect top-down (global) studies to bottom-up (ecosystem) analysis. Reduction in scale may also be possible with more time averaging and using other information such as campaign data or local measurements.

Discussion of the time scale for determining CO_2 fluxes agreed that monthly values are necessary to resolve the seasonal cycle, which is a critical variation. It was also noted that interannual variability at any location is high both for biological forcing parameters and transport systematic variation, e.g., variations in weather patterns may persist for seasonal time scales producing variations in transported CO_2. Decadal data from mid latitudes, e.g., Harvard Forest, suggest at least 4 years of data are required to produce a representative annual mean.

Quantitative goals for the accuracy of inferred fluxes were proposed. A starting point would be the Rayner and O'Brien crossover point of 2.5 ppmv precision for column CO_2 on an 8x10° monthly averaged basis. A goal of obtaining CO_2 flux distributions to an accuracy of 20% on a 10^7 km^2 grid with monthly time resolution was discussed. An alternate proposal was to aim for 20% uncertainty on the annual mean flux and propagate that to a monthly requirement. Resolving annual fluxes to 20% is roughly equivalent to 0.5 Pg/yr, which is a desirable level of accuracy for regional studies. The goal could be phased, e.g., 20% at 10^7 km^2 in the 3-5 year time frame and 15% at 10^6 km^2 in 10 years. This goal needs further consideration.

A caution was raised that these numbers need to be stated in a way that reflects the subtlety of biosphere/atmosphere interactions for example. They are not simply engineering specifications. They need to put in terms of hypothesis testing that leads back to scientific objectives. For example, one general hypothesis is that climate variability effects C cycle variability. We also need to keep in mind the benefits of associated local measurements to anchor the satellite data.

Discussion then turned to define requirements for sensitivity, accuracy, and precision of measurements to infer fluxes. Primary is atmospheric CO_2 concentrations. A major question is the extent to which vertical profile resolution is required versus a column CO_2 measurement. Obtaining profile information in the lower atmosphere from space is technically very challenging.

Tests of measurement requirements are being done based on data from AIRS, which expects to retrieve CO_2 concentrations weighted to middle troposphere. In one test, assuming an AIRS-like inversion with 1.5 ppm rms error did not add much to existing flask information because of problems in inferring H_2O, T, and CO_2 from top-of-the-atmosphere radiances [Denning et al., in press]. A CO_2 profile weighted at 400-800 mb is far from ideal. Aircraft data over continents suggest that the measurement at 500 mb won't see the surface on a monthly basis in a coherent way. However, modeling suggests that regional-scale features are present at 500 mb in some areas. The phase lag of the CO_2 seasonal cycle at 500 mb relative to the surface is significant. In contrast, the 800 mb level is in contact with surface almost daily. It was noted that AIRS is an existing instrument that will soon be deployed and that even though AIRS has not been optimized for measuring CO_2, AIRS analysis may provide valuable information for other proposed techniques. The baseline AIRS mission won't invest much effort in getting CO_2 retrievals unless this group shows interest (i.e., it's not free). Primary AIRS products are T and H_2O at 50 km resolution. Proposed CO_2 data product is 350-800 mb, 2-3 ppm every 50 km under clear conditions. The additional cost for retrieval of CO_2 is 15% of the execution time for

core product. Next effort is to get partially cloudy areas and a gridded product at some spatial and temporal resolution.

In relation to ocean carbon objectives, satellite CO_2 measurements will not resolve gradients near to ocean surface for inferring air-sea fluxes in the foreseeable future.

A proposal was briefly floated to narrow the scope of the GCCP to developing remote sensing measurements for terrestrial and marine biomass productivity, and atmospheric CO_2. A consensus developed that starting from a measurement perspective may be putting the cart before the horse and that our objective isn't to do remote sensing, it's to solve C cycle problems. However, it was recognized that remote sensing is where NASA can make its biggest contribution.

Discussion continued on the need for CO_2 vertical profile measurement. It is generally accepted that profile information is highly desirable to better constrain the flux problem, but we are not currently able to place quantitative requirements on it. We may need to put in a place-holder pending further model studies so it doesn't fall off the table for the 10 yr time frame. One possibility for vertically resolved profiles that has been discussed is a 3-level resolution: 0-3km, 3-6 km, 6 km and above. In such a strategy it is important that the lowest layer be deep enough to include the maximum depth of PBL to avoid aliasing.

The GCCP should consider a phased approach to resolving these issues. In the near term, sensitivity testing should be done to establish requirements. Planned and existing measurements (e.g., AIRS) should be analyzed to see how they influence flux calculation uncertainties. Finally the impact of new measurement systems must be analyzed. These include both column and profile CO_2 measurements. It is quite feasible that column and profile instruments should be flown together. Since costing estimates need to begin relatively soon, different options must be scoped. Aircraft demonstration instruments should be developed to test the ability to retrieve science-quality data in real cloudy and aerosol-laden atmospheres. Such prototype instruments may also help to scale up results from local and regional field measurements and campaigns.

Discussion moved on to the other main component of inferring fluxes from concentrations: transport models. Although the problem is currently seen as being limited by availability of CO_2 data, a significant degree of uncertainty for inferred fluxes may be contributed by transport errors. Within the current model framework, which is based on climatological spatial patterns, a primary result from TransCom is that subgrid-scale vertical transport is a major factor distinguishing one model from another rather than advection scheme. Model extremes for CO_2 flux inferred from the same data are TM2 and TM3, both of which are driven by European Center for Medium Range Weather Forecasts (ECMWF) analyzed winds. One of these models stratifies concentrations and the other mixes vigorously. TRANSCOM models generally agree in source regions. Inversion is more tolerant of errors in winds when using column CO_2 than for profiles according to Rayner and O'Brien (2001). TRANSCOM bottom line to this point is that errors arising from poorly sampled atmosphere are larger than the differences among models. Statement was made that other groups will be defining missions targeted to improve forward modeling of fluxes. A goal of the GCCP will be to provide measurements to better constrain fluxes derived from these models.

A lot of work in general circulation modeling needs to be done here: e.g., boundary layer turbulence, convective mixing. Additional species should be measured to improve these processes. Improvement of transport modeling is recognized by GCM crowd, by people studying ENSO, atmospheric chemistry, and the climate community. So, in this context, the GCCP can bank on others to do some of this work.

Within the 10-year program timeframe, data assimilation will be an important tool in simulating CO_2 transport and inferring fluxes. Specific areas for improvement include the representations of vertical transport and further development of data assimilation methodology. Coordinated model development between assimilation and tracer transport has been proceeding in the stratosphere for a decade. Assimilation can also give information on error, which is not being fully exploited currently.

The model development needs to be done in synergy with assimilation and satellite observation strategy. Modeling needs will evolve as data becomes available. SF_6, radon and other tracers (e.g., CO, HCN) would help this effort. Regular measurements are more useful for model evaluation suggesting monitoring type measurements rather than intensive campaigns. An example is found in 500-mb animations that show huge CO_2 fountains associated with monsoons. Correlation between seasonal fluxes and vertical mass flux could be tested with CO_2/radon ratios. Other tracers would also work. We should design from scratch the tracer payload for enhancing the satellite data. Need data assimilation technical development in parallel with instrument development. Data assimilation will include concentrations, fluxes, and processes. In 10 yrs we should be able to assimilate down into the process level models. No one currently has a mandate for this. A good understanding of assimilation of aerosols information (e.g., MISR) is also desirable.

Autonomous, regular vertical profiles of high-accuracy CO_2 on a 10 yr time scale could serve to 1) provide CO_2 profiles for validating satellite measurements and 2) transport parameterization improvement. Autonomous instruments on commercial aviation flights may be one answer, although most data would be in upper troposphere. Development of technology for inexpensive, readily deployable CO_2 instrument should be considered. Mesoscale model may be needed for validation studies with local data. The CO_2 Budget and Rectification Airborne experiment (COBRA) field measurements do analysis with wind products on scale of 40 km rather than 1 degree.

Current DAO activities in conjunction with NCAR involve data assimilation and a "national" biogeochemical model. Need to develop biogeochemical capability in NASA data assimilation models. DAO is already oversubscribed. To focus on carbon they would need to expand mandate and add new people. Ocean modeling also needs to be developed as a part of the assimilation effort. Assimilation efforts need to be competed.

Atmospheric chemistry related to CH_4 and CO belongs in the GCCP to some extent both for better understanding of CO_2 and for its role in climate forcings other than CO_2. However the main emphasis on chemistry will come in other NASA programs, e.g., ACMAP, with whom we will coordinate. Full reactive chemistry is going to be done for other reasons, e.g., tropospheric O_3. CO and CH_4 satellite observations are going to become available from MOPITT and TES. We should examine the extent to which coordinated observations of CO and/or CH_4 are needed along with CO_2 to understand the carbon budget.

NASA has capabilities for measuring CH_4 and we should investigate what can be done to constrain C cycle with CH_4 data. CH_4 budget is a difficult problem because sources (landfills, rice paddies, etc.) are hard to quantify. Some analysis is taking place within the chemistry community, but not to the scale of the ozone problem. The part of the CH_4 cycle that is tractable is the connection to CO_2. Counting cows is not tractable. Wetland CH_4 emissions, which could become CO_2 emissions if wetlands get warm and dry, should be studied. We want to study CH_4 concentrations at high latitude, e.g., ~70°, and to look for hydrate destabilization. Spatial

variations of column CH_4 could potentially be used to isolate stratospheric from tropospheric influences on column CO_2 variation, e.g., changes in tropopause height.

CO is mainly of interest to determine fossil fuel component of carbon flux. It is also an important diagnostic for biomass burning (fire) carbon sources. Fires are a major source. In august, fossil fuel is about 10% of biospheric uptake of CO_2 so other tracers (CO, etc.) are required to isolate fuel component. Because of the point source nature of emissions and since the lifetime of CO is days to weeks, these measurements need to be made at high spatial and temporal resolution. MOPITT profile information may not be sufficient to identify sources. TES data will have better vertical resolution, about three layers in the troposphere. The possible requirement for CO data should follow a track similar to that described above for CO_2 data: model sensitivity testing, analysis of current capabilities, and impact of new instrumentation.

For carbonaceous aerosols, the GCCP should mainly point to other programs, but we need to make sure the derived info makes sense in the C cycle context. For example, carboneous aerosols are asserted not to be a major component of atmospheric carbon budget, but has this been quantitatively proven? Aerosol, along with CO, is useful for constraining biomass burning and fossil fuel burning carbon sources. Carbonaceous aerosol is not expressly a major focus of NASA aerosol climatology project at present.

Initial discussion of isotopes concluded that they are highly desirable to understand processes contributing to source/sink distributions. ^{18}O helps distinguish between photosynthesis and respiration contributions to net flux. For example, they could be used to detect increased sink associated with CO_2 fertilization and lifetime in various reservoirs—litter, etc. ^{13}C has an air-sea exchange signal. The measurement of these species from space with today's technology is, however, not feasible with sufficient precision to advance our knowledge of carbon cycle. NASA should argue instead for a lightweight, easily deployed in situ sensor to be used in support of remotely sensed CO_2. This would be a possible area for technology development.

Brief discussion of implementation strategy for isotope analysis concluded that CO_2 isotope information for ^{18}O must be coupled to water isotope information in rain and vapor because ^{18}O in CO_2 depends on the isotopic composition of the H_2O in which the CO_2 was last dissolved. We can connect to other programs, e.g., International Atomic Energy Agency /Global Network for Isotopes in Precipitation, for measurements of deuterium and O isotopes in rain.

Land (Workshop 1)

J. Collatz (chair), F. Hall (rapporteur)

The proposed NASA GCCP seeks to address NASA's contributions toward accomplishing the long term goals set out by the USGCRP Strategic Plan. These goals as they relate to a focus on land surface processes can be summarized as follows:

1) Quantify North American carbon sources and sinks
2) Report the state of global carbon cycle on an annual basis to inform decision makers/stake holders
3) Evaluate impacts of land use change and management practices on net carbon fluxes
4) Forecast future atmospheric CO_2 concentrations and terrestrial sources and sinks
5) Provide scientific underpinning and evaluations for management of carbon in the environment

These goals are ambitious but highly relevant to societal questions regarding human impacts on future climate change, resource management and ecosystem health.

Discussions during the workshop repeatedly acknowledged that land use history and current land management practices are likely to be significant carbon sinks. These processes manifest themselves as sinks through the accumulation of biomass and/or soil organic matter. In order to locate, understand and predict changes in terrestrial carbon stocks with useful accuracy, remote sensing measurements need to be expanded and linked to field studies and models.

1) Biomass

A top priority measurement identified in workshop discussions is biomass, both absolute amount and change quantification. Remote sensing can provide systematic, global measurements at fine spatial resolution of above ground biomass. No plausible approaches for directly measuring below ground biomass and soil organic matter via remote sensing techniques are now available. However, total biomass and soil organic matter are related to above ground biomass, land cover and land cover history so improved understanding of the relationships between above ground biomass, total biomass, soil carbon and land cover classification will increase the utility of feasible satellite measurements.

Carbon contained in above ground vegetation globally is currently estimated to be about 400 Pg with an uncertainty of about 100 Pg. A reduction in this uncertainty to about 2 Pg is desired in order to adequately address source/sink issues. The amount of biomass present is a measure of the potential contributions of the land surface as a source or a sink whereas changes in biomass reflect current sources and sinks. To estimate regional changes in above ground biomass adequately a measurement accuracy on the order of about 5 tons of carbon per hectare per year is needed. Biomass changes at scales commensurate with land use change, natural and anthropogenic disturbance and climate variability are needed. These scales vary from a few meters in some regions such as tropical forests to tens of kilometers at boreal latitudes where fire is a major disturbance.

It was noted during discussions at the workshop that biomass changes are typically characterized by abrupt large decreases and by gradual increases. Thus detection requirements for measuring disturbance are generally lower than those for measuring biomass accumulation caused by such things as regrowth and woody encroachment.

The relationship between observed changes in above ground biomass and net carbon flux depends on the type of land cover and its disturbance and management history. Thus a combination of improved biomass change estimates, improved capability to identify the state of land cover and a better understanding of the relationship between land cover state and net carbon fluxes will greatly reduce uncertainty in estimates of current and future carbon sources and sinks on the land surface.

Intensive field-airborne-remote sensing campaigns in areas of major disturbance of terrestrial ecosystems will be needed to support satellite/sensor/algorithm development and process level understanding. In particular, NASA expects to take advantage of existing in situ data collecting activities carried out by other agencies (e.g., Forest Inventory and Analysis Program, Long Term Ecological Research Sites, USDA agricultural surveys) and partner with other agencies in conducting new field studies.

Some of the discussion on biomass measurement addressed the potential for combining lidar and radar instruments on the same platform. The lidar measurements would provide more

detailed canopy structural information and enhance interpretation of concurrent radar measurements. Radar, in turn, would be able to provide global coverage on a sub-annual basis.

2) Land cover classification

Land use history is thought to be one of the primary causes for the reputed North American carbon sink. Since the beginning of this century many wooded areas that were deforested for wood products and converted to agricultural uses have been regrowing because of the abandonment of marginal agricultural land and centralization of agriculture in non-forested regions. This has led to accumulations in biomass and soil organic matter. The rates of biomass accumulation are dependent upon the age since abandonment and subsequent management practices. Another mechanism attributed to the carbon sink is fire suppression which has allowed some ecosystems to accumulate woody material that would otherwise have burned off at the natural, more regular frequencies.

More accurate and finer detailed land cover observations coupled with improved models of the relationship between land cover and net carbon fluxes would help to quantify current sources and sinks and provide information for assessing how land cover history will affect future sources and sinks. Much algorithm development, validation and in situ process studies will be needed to express land cover classes in terms of their net carbon fluxes. These efforts should be coordinated to exploit existing data sets and field studies as well as help define new in situ studies.

Systematic fine spatial resolution (<30 m) global coverage is required at annual intervals if annual reports of the state of the carbon cycle (Goal 2 of the USGCRP Long Term Strategic Plan for the Carbon Cycle) is to be achieved.

Most of the remote sensing methods proposed for measuring above ground biomass (see #1 above) are based on measurements of canopy structure and, therefore, provide additional information that can be used to classify land cover types when used in combination with traditional multi-spectral approaches. The combination of above ground biomass and land cover classification would lead to improved estimates of total biomass and improved accuracy and resolution of land cover classes.

3) Disturbance

Satellite observations provide unique capabilities for estimating fires, pest mortality, and storm mortality at regional to global scales. Current missions such as Landsat-7 and Terra are capable of estimating such disturbance at sufficient temporal and spatial scales. Two important remaining issues are the incompleteness of algorithms/models capable of producing carbon fluxes from remote sensing signals and the assurance of long term continuity of these measurements.

4) Productivity

The net CO_2 exchange from land surfaces is controlled by photosynthetic uptake by vegetation (productivity), respiration/decomposition from soils, fires, harvest export and local fossil fuel emissions. Imbalances between vegetation productivity and decomposition can produce regional to global sources or sinks. The rate at which CO_2 is increasing in the atmosphere varies at seasonal, interannual and longer time scales because of these imbalances. The mechanisms responsible for seasonal variability are fairly well understood: in spring in northern latitudes photosynthesis exceeds decomposition as photosynthetically active radiation

(PAR) and air temperatures increase and soil temperatures lag behind while in late summer to early winter warm soils drive decomposition to exceed photosynthesis. The mechanisms underlying interannual variations and long term trends in the atmospheric CO_2 growth rate, however, are not known and may be different for each time scale of variability.

Discussions acknowledged that space based atmospheric CO_2 measurements especially in combination with CO measurements at appropriate horizontal, vertical and temporal scales could be used to estimate net CO_2 exchange and respiration/decomposition. The subject of atmospheric CO_2 measurement requirements, however, was deferred to the atmosphere breakout group.

Current satellite technology is used to estimate the amount of PAR that is absorbed by vegetation canopies which is a primary driver of photosynthetic CO_2 uptake, the sink component of the net CO_2 exchange. Over periods of about a year or more carbon input from photosynthesis exerts control on respiration/decomposition, on harvest export and on fire fuel loads.

Productivity also depends on the efficiency with which absorbed PAR drives CO_2 uptake and is a function of the type of vegetation, the availability of nutrients and stress levels (e.g. drought, cold temperatures, etc) among other things. Efficiency is not yet observable from space but potential methods have been proposed including passive multi- spectral signatures and laser induced fluorescence. Though not discussed at this workshop, previous assessments (GTOS) of measurement requirements for accuracy of productivity measurements from satellites defined a minimum requirement of better than 20% and a goal of 10%.

Respiration/decomposition occurs mostly at the soil surface and below making it much less amenable to remote sensing measurement approaches. However, remote sensing methods for estimating surface soil moisture and the freeze/thaw state of the soil have been proposed and such measurements would contribute to better predictions respiration/decomposition by providing knowledge of environmental conditions that control these processes.

Each of science topics that came out of the workshop discussions and summarized (biomass, land cover, productivity, disturbance) can be easily mapped to each of the USGCRP Carbon Cycle long term goals. The GCCP focuses on providing new critically needed space based measurement capabilities and supporting efforts (data/information products) in a timely manner to provide the science community and policy makers/stake holders with information of societal and scientific relevance.

Oceans (Workshop 1)

W. Gregg (chair), S. Signorini (rapporteur)

Attendees:	David Adamec	Mike Behrenfeld	Mary-Elena Carr
	Carlos Del Castillo	Lisa Dilling	Richard Feely
	John Marra	Chuck McClain	Rick Miller
	John Moisan	Tiffany Moisan	Keith Moore
	Michele Rienecker	Jim Yoder	

The Ocean Carbon Working Group (OCWG) met twice on Jan. 10, 2001, as part of the first GCCP workshop. The objectives at this workshop for the OCWG were limited:

1) Define the specific scientific objectives of the GCCP, and where possible, the scientific accuracies and spatial and temporal resolution required

2) Define potential methodologies to achieve the objectives

The OCWG defined 3 overarching scientific objectives for the GCCP:
1) What is the seasonal-interannual-interdecadal variability of ocean carbon fluxes at basin scales and at the level of $\pm$ 0.1Pg C/yr?
2) What controls the magnitude and variability of ocean carbon?
3) What are the scientific consequences of changes in the global carbon cycle on ocean carbon cycling processes?

The OCWG developed a comprehensive list of specific scientific objectives that included information on a set of ocean, atmospheric and terrestrial variables that is necessary to meet the overarching objectives. Where possible, accuracy requirements were defined and a suite of tools to enable measurement or greater understanding of the variables was defined. If the required variable is the domain of discipline other than the ocean carbon community, methods for providing the required information are left to the discretion of the other community.

Specific Objectives
To meet the requirements and accuracies of the overarching objectives, the OCWG will require:

Requirement: delta pCO_2
Justification: required to understand carbon flux
Accuracy: 2-5 µatm
Methods:

Requirement: atmospheric CO_2 at the surface
Justification: required to evaluate delta pCO_2
Accuracy: 1.5 ppm column
Methods: left to atmospheric measurement community

Requirement: ocean pCO_2
Justification: required to evaluate delta pCO_2
Accuracy: 2-5 µatm
Methods: direct measurement by in situ sampling
multiple sensor remote sensing approach using relevant and related parameters (SST, SSS, chlorophyll, etc.)

Requirement: ocean SST
Justification: required to evaluate ocean pCO_2 and primary production
Accuracy: 0.1°C
Methods: left to NASA, NOAA remote sensing communities

Requirement: sea surface salinity
Justification: required to evaluate ocean pCO_2
Accuracy: 0.1 PSU
Methods: left to physical oceanography community

Requirement: ocean mixed layer depth

Justification: required to evaluate pCO_2, ocean circulation, primary production, light availability in oceans for phytoplankton growth
Accuracy:
Methods: technology development
remote sensing
data synthesis (T, S)
modeling
data assimilation of T, S
in situ observations

Requirement: primary production
Justification: required to evaluate formation of POC
Accuracy:
Methods: remote sensing of chlorophyll, long-term time series required
models (diagnostic, prognostic, and empirical)
data synthesis (SST, PAR)
laboratory analysis of physiological mechanisms
model intercomparison

Requirement: ocean carbon export
Justification: required to evaluate loss of POC
Accuracy:
Methods: in situ sampling (sediment traps, isotopic analysis)
remote sensing (altimetry, particulate lidar)
data synthesis
models
assimilation of related variables

Requirement: ocean circulation
Justification: required to evaluate spatial and temporal variability of pCO_2, primary production, carbon export, irradiance availability, distributions of biomass, POC, and DOC
Accuracy:
Methods: left to physical oceanography community

Requirement: sea ice distribution
Justification: required to evaluate CO_2 exchange distributions
Accuracy:
Methods: left to sea ice community

Requirement: ocean calcification
Justification: required to evaluate pCO_2 through changes in pH
Accuracy:
Methods:

Requirement: ocean nitrogen fixation

Justification: required to evaluate chlorophyll biomass, POC, and primary production
Accuracy:
Methods:

Requirement: ocean dissolved organic carbon concentration
Justification: required to evaluate pCO_2 and total organic carbon
Accuracy:
Methods:

Requirement: ocean phytoplankton biomass
Justification: required to evaluate pCO_2, POC, primary production, and export
Accuracy:
Methods: remote sensing
algorithm development to further refine observations

Requirement: ocean nutrient concentrations (N, P, Si, Fe)
Justification: required to evaluate primary production
Accuracy:
Methods: algorithm development
remote sensing (chlorophyll, fluorescence)
data synthesis
in situ observations
models
data assimilation

Requirement: phytoplankton functional group distributions (diatoms, green algae, coccolithophores, cyanobacteria, diazotrophs, dinoflagellates
Justification: required to evaluate distributions and fate of POC
Accuracy:
Methods: remote sensing of visible spectra and fluorescence
in situ observations (optics, fluorescence)
modeling
data synthesis (T, S, MLD)

Requirement: surface irradiance
Justification: required to evaluate primary production, and formation/destruction rates of colored dissolved organic matter (CDOM)
Accuracy:
Methods: left to atmospheric and radiative transfer communities

Requirement: ocean chromophoric dissolved organic matter
Justification: required to refine observations of chlorophyll, POC, and primary production
Accuracy:
Methods:

Requirement: soil type and moisture

Justification: required to evaluate delta pCO_2
Accuracy:
Methods: direct measurement by in situ sampling

Requirement: gas transfer across the air-sea interface
Justification: required to evaluate air/sea CO_2 exchange
Accuracy:
Methods: algorithm development (using laboratory analyses (wave tanks) and in situ observations)
models

Requirement: sea foam distributions
Justification: required to evaluate air/sea CO_2 exchange
Accuracy:
Methods: left to physical oceanography community

Requirement: sea surface surfactant distributions and quality
Justification: required to evaluate air/sea CO_2 exchange
Accuracy:
Methods: left to physical oceanography community

Requirement: air stability
Justification: required to evaluate air/sea CO_2 exchange
Accuracy:
Methods: left to physical oceanography community

Requirement: surface wind speed
Justification: required to evaluate air/sea CO_2 exchange using current gas exchange calculation methodologies
Accuracy: 0.5 m s^{-1}
Methods: remotely-sensed
data synthesis

The OCWG also strongly recommended the formation of active Calibration/Validation activities under the auspices of the GCCP. This calibration and valication team would have 4 main responsibilities:
1) assure accuracy of derived carbon variables in the traditional manner of calibration and validation activities
2) assure seamless time series of derived carbon variables for long-term remote sensing observations – this is an activity that does not fall within the purview of individual missions but is critical for understanding natural variability
3) provide estimate of errors and error length scales of carbon-related variables – this is important to characterize natural variability but also to support data assimilation
4) assure, adhere to, and develop standards for measurement, sampling, and handling of carbon-related variables – this assures consistent and accurate observations, and may be established through partnerships when possible.

On the question of what are the consequences of changes in atmospheric CO_2 on ocean carbon cycling processes, the OCWG listed several potential required observations, but the list was not intended to be exhaustive. They included:

-- changes in deposition of nutrients
-- precipitation
-- eutrophication
-- warming
-- calcification
-- N fixation
-- sea level
-- changes in pools of organic carbon
-- changes in functional group distributions

A5.2. Workshop 2 (March 20 - 22, 2001)
Atmospheres (Workshop 2)
A. Andrews (chair), Chris Barnet (rapporteur)

Attendees:	S. Ismail	L. McMillin	D. Crisp
	R. Engelen	J. Bacmeister	J. Abshire
	R. Chatfield	C. Miller	L. Strow
	S. Pawson	P. Caruso	M. Suarez
	R. Dahlman	F. Hall	J. Randerson

Workshop Overview: Breakouts were along discipline lines: atmospheres, oceans and land. Groups were charged with defining a timeline of activity blocks that can be costed. Day 1 discussion emphasized "technology", while day 2 emphasized "science products". The rationale for this structure was to ensure that adequate time would be allotted for issues associated with development and deployment of technology. Discussion in the atmospheres group was focused primarily on development and validation of techniques for spaceborne measurement of atmospheric CO_2 mixing ratios. Based on recent modeling studies and the discussion from Workshop 1, we started from the assumption that CO_2 data with long-term precision equal to or better than 0.3% (1ppm) is desired.

Day 1
Technology and strategy for developing techniques for space-borne CO_2 measurements

The initial discussion addressed whether there is a need for carbon-cycle specific programs based on the IIP, ESSP and NMP. Participants identified at least four distinct passive and two active approaches for measuring CO_2 that warrant development:

Passive:	Grating Spectrometer	optical (e.g., 1.58 or 2 μm)
	Scanning Fabry-Perot Interferometer	
	Fixed FPI	
	Limb-sounding Fourier Transform Spectrometer (FTS)	
	*Grating Spectrometer	thermal
	*FTS	thermal

Active:	Total Column Laser Sounder Profile Lidar	optical

*The thermal techniques are comparatively mature, but are not expected to be as sensitive as optical methods to variations in CO_2 at the surface.

More detailed information is not available at this time, since many groups are proposing to the current IIP and ESSP and are reluctant to share competition sensitive details. In general, these methods will require concurrent observation of O_2 or another well-mixed gas in order to account for variations in air density caused by topography and varying amounts of water vapor. The methods listed above have a number of competing/complementary pros and cons. Passive techniques have the advantage of higher technology readiness levels and will be relatively inexpensive. Optical methods (either passive or active) are weighted according to density and are thus most sensitive to variations at the surface, while those using emission at thermal wavelengths will be sensitive to higher altitudes. For example, the vertical weighting function for the AIRS instrument has a maximum in the 300-800 mb range. Active techniques have the potential for flying in a sun synchronous dawn-dusk orbit, which would reduce potential bias associated with diurnal variation of CO_2 in the planetary boundary layer. Active techniques employing ranging may resolve several vertical layers and would be able to detect clouds in the instrument field of view, but this will require improved technology (e.g., telescopes, lasers, amplifiers). In contrast, most of the passive methods are based on existing technology. The consensus of the group was that active sensors will require a few years to achieve TRL levels that meet ESSP requirements, but that passive approaches are good candidates for the current ESSP call. If a goal of the GCCP is to develop technology for remote sensing of CO_2 that can be used for long-term monitoring (possibly by another agency), then it seems wise to pursue as many of these approaches as funding will allow. The diversity of possible techniques and their distinct advantages and disadvantages is sufficient to justify taking 5-10 concepts to the aircraft demo stage. An average expenditure of $1M/yr for 3 years per instrument would total $15-30 M, which is small compared to the cost of developing and launching a single instrument. Instruments for measuring O_2 or other another gas for the purpose of obtaining CO_2 mixing ratios should also be included in this program.

Note that the technology readiness levels for some of the methods listed above do not fall neatly into the realm of IIP, NMP or ESSP, so it may be necessary to broaden the program guidelines. A CCI-specific program to support airborne demo versions of these instruments should begin as soon as new funding is available, followed by a satellite proof-of-concept program 2-3 years later. The airborne demo instruments would be extremely useful for testing algorithms under a variety of atmospheric conditions and could be used for validation of subsequent satellite sensors and would add value to field studies designed to connect experiments with varying spatial scales, i.e., tower to aircraft to satellite.

The AIRS instrument is currently scheduled for launch in late 2001. Although AIRS was not designed to measure CO_2, it is expected to be able to retrieve mean CO_2 mixing ratios between 300 and 800 mb with an accuracy of 2-3 ppm for individual profiles with footprint of 50 x 50 km. Because AIRS and follow-on instruments are already scheduled for continuous deployment over the next decade, they offer the potential of a long-term record of CO_2 at minimal cost. Other instruments that may be able to retrieve CO_2 include SCIAMACHY, TES and Improved Atmospehric Sounding Interferometer (IASI). Support may be needed for algorithm development, validation, and assimilation of these data.

Finally, modeling work to evaluate the potential of proposed measurements to reduce uncertainties on estimates of CO_2 sources and sinks should be supported so that the optimal measurement strategy can be designed. Some of this work will necessarily be the responsibility of individual instrument teams, but there is also a need for independent, objective analysis by members of the science community who are not associated with a particular instrument. Modeling work is also needed to address the issue of whether existing methods for measuring CO and CH_4 will have sufficient accuracy and resolution for detailed studies of carbon cycling and whether CO and CH_4 observations collocated with CO_2 data are required. A rough order of magnitude investment for technology-related modeling was ~10 FTE's (full-time equivalent) based on a few separate groups doing algorithm development and measurement impact studies. Some of these people might be supported in part by the IIP-like program discussed above. In the near term, some effort should be invested in making a variety of model fields available to investigators for algorithm development. Modeling resources will also be needed to support field campaigns. A workshop in 2001 or 2002 was proposed to design a strategy for meeting the modeling needs of the measurement community. This may be a part of a larger workshop devoted to a broad range of modeling and data assimilation issues relevant for the GCCP. See the discussion of Day 2 breakout for more details.

Calibration and Validation Ancillary and Corroborative Measurements:

The discussion then moved toward outlining a strategy for calibration/validation of proposed space-borne techniques and what other technology might be needed for process studies. The development of space-borne CO_2 sensors with long-term precision better than 0.3% (1 ppm) will require basic lab spectroscopy. Work is also needed for O_2 in order to obtain the dry air mixing ratio of CO_2. N_2O is another possible candidate for measuring air density, and the spectroscopy of CH_4 is complex and warrants further study in the context of carbon cycle research. Rough cost estimates were ~100 K /yr x 3 groups for CO_2 and O_2 and/or N_2O and ~200 K/yr x 3 groups for CH_4.

The deployment of up-looking spectrometers and lidar instruments would be a logical step toward space-borne measurements. Currently, up-looking FTS's with sufficient spectral resolution and range are being operated at several locations, including the Oklahoma Atmospheric Radiation Measurements/Cloud and Radiation Testbed (ARM/CART) site and from Mauna Loa. Existing data from these instruments could be analyzed to retrieve CO_2 using both thermal and optical bands. The accuracy of column CO_2 retrievals could be tested by obtaining vertical profiles of CO_2 in the field of view of the spectrometers, using a fast-response airborne in-situ sensor such as those operated by Stephanie Vey and Steve Wofsy. For the purposes of validation of upcoming and proposed satellite instruments, it would be desirable to augment other ARM/CART and/or NOAA CMDL sites with up-looking spectrometers at a rate of 1-2 new sites per yr. Estimated costs are $250K per spectrometer plus support. As lidar technologies advance, up-looking lidar instruments could also be deployed at these sites as needed.

Cheap, expendable CO_2 sensors that could be flown routinely on small balloons would also be powerful assets for satellite instrument validation and for connecting column observations to surface data from the NOAA CMDL sampling network. To be useful, such an instrument would need to achieve better than 1ppm accuracy over at least the lowest few km of the atmosphere. The development of such a sensor would seem to be ideally suited for an SBIR.

CO_2 relevant measurements should be added to existing and upcoming satellite validation efforts (e.g., Aura, Aqua, Terra). Up-looking FTS instruments and airborne in situ or flask CO_2 and O_2 measurements would be valuable. The possibility of adding an up-looking FTS and aircraft flights to existing plans for the LBA experiment for the purpose of validating the AIRS CO_2 retrieval should be explored.

There will eventually be a need for GCCP specific validation campaigns. Ideally, these could be combined with experiments designed to study process studies. An airborne sensor intercomparison would be needed to determine which of the methods taken to the airborne demo level are best suited for satellite missions. Aircraft instruments resulting from the current IIP call should be ready for deployment in time for the proposed IWG North American carbon budget experiment which will likely occur between 2003 and 2006. In addition, there may also be satellite column observations available as early as 2005, if an ESSP is awarded this round. Validation mission(s) for CO_2 satellite observations will be required over a wide range of latitudes over a variety of terrain and vegetation types with good seasonal coverage.

Finally, the question was raised whether the GCCP should support development of instruments that are not necessarily headed for space. For example, there is currently no known method by which space-borne remote sensing techniques could be used to measure rare isotopes of CO_2, but fast-response in situ measurements from aircraft are possible and would be valuable for regional scale process studies. Similarly, fast-response in situ O_2 instruments for aircraft are needed for validation of the O_2 component of proposed CO_2 satellite sensors and would provide independent information about the CO_2 budget.

Day 2

Science

Datasets

The breakout session began with a discussion of what data is likely to become available within the next decade. The attached timeline was produced.

Modeling

The modeling component of the GCCP is not as well defined as the measurement aspects. While the GCCP should not encompass all of carbon cycle modeling, it is necessary to ensure that NASA's modeling needs are met. These needs can be subdivided into five broad categories with substantial overlap:

1) OSSE's for instrument design and algorithm development
2) measurement impact studies to design optimum sampling strategy
3) data assimilation
4) theory and meteorological support for field campaigns
5) prediction (e.g., future atmospheric CO_2 loading, carbon cycle/climate connections)*

*The prediction element was not discussed during the workshop, but will clearly be a focus of carbon cycle research in the next decade.

The extent to which measurement impact studies and OSSE's simulate real-world sampling conditions will be limited by the underlying models. Currently, parameterizations of the diurnal variation of the planetary boundary layer and convective transport in most models of atmospheric transport models introduce large uncertainties into studies of CO_2 sources and sinks. If, for example, diurnal variation of CO_2 is not reproduced by a model used in an OSSE or measurement impact study, a particular measurement approach or sampling strategy may appear

to be artificially good (or bad). Questions addressed included to what extent OSSE's should be the responsibility of the individual instrument teams versus a core independent effort that would strive to evaluate different concepts objectively. Clearly, OSSE's are needed for algorithm development by the investigators, but studies to determine what types of sampling are most effective for constraining estimates of sources and sinks will be needed and should be done by scientists who do not have a vested interest in a particular technique. Work should also be done do investigate whether collocated observations of CO and CH_4 would add significant value to a CO_2 satellite mission.

There was discussion as to whether effort should go into building a flexible community carbon model comprised of interchangeable modules, or if multiple independent models should continue to be developed. The balance between maximizing progress driven by competition and minimizing redundancy is an issue for the modeling community at large. This topic was also brought up in the Day 3 plenary, and is unlikely to be resolved before the GCCP is delivered. However, it seems likely that effort will need to be focused on developing one or two models for assimilation of GCCP data. The possibility of a collaborative effort between NCAR and the NASA DAO was discussed. Opportunities for collaboration with NOAA should also be explored.

A distinction was made between GCM's used for assimilation and models used in inversion studies where observed concentrations are used to constrain surface fluxes. It was stated that the resolution and scales relevant for assimilation and inversion are fundamentally different. However, these differences may be an outgrowth of the fact that inversion studies to date have been constrained primarily by data from the NOAA/CMDL cooperative air sampling network, which has limited spatial and temporal coverage. Thus, this distinction may become blurred with the availability of global CO_2 fields. Clearly, both types of models will need to have the best possible representation of the underlying physics.

Atmospheric transport simulations contribute significantly to the uncertainty in estimates of surface fluxes. The TRANSCOM-3 model intercomparison showed that the variation in flux estimates resulting from different atmospheric transport models is large. The breakout group identified the representation of the planetary boundary layer and of vertical transport by convection as important factors limiting the accuracy of inversions. These issues are also likely to be important for data assimilation. However, it should be noted that improved atmospheric transport simulations are important for problems not associated with the carbon cycle, e.g., evolution of pollution plumes, tropospheric O_3, etc. Thus, we need to identify modeling efforts that are currently underway or planned and contribute to them as needed to make sure that issues relevant for OSSE's, measurement impact studies and data assimilation are met. This is the line-item for general model improvement in a modeling activities timeline.

It was noted that the data provided by the NOAA CMDL network is not easily incorporated into traditional data assimilation models. Data with nearly global coverage every few days is required. Work is currently being done by the Goddard DAO on methods for assimilating AIRS data when it becomes available. Output from the AIRS OSSE is being used to explore how that data can best be incorporated. Similar effort will be needed as new data products become available over the next decade. There should also be effort invested in coupling biogeochemical models with models to be used for assimilating CO_2 data e.g., so that fluxes can be assimilated as well as concentrations.

Finally, meteorological and theoretical support will be needed for upcoming field campaigns. This may include flight planning for Lagrangian experiments where an air mass is

followed as it passes over a particular type of ecosystem or attempting to quantify convective outflow. Regional scale models will be needed for the location of the field campaign. Some such models currently exist, but may need to be adapted depending on the goals of the experiment (e.g., coupled to biogeochemical models). Funding will also be needed so that theory teams can accompany the experimenters into the field.

The group's estimate of personnel needed to accomplish NASA relevant modeling goals totaled ~110 FTEs over 10 yrs with effort and funds shifting among OSSE's, measurement impact studies, data assimilation, and support of field campaigns as needed.

Field Experiments

The last part of the discussion focused on opportunities to combine calibration and validation activities and process studies. The LBA experiment currently underway in Brazil is planned to go through 2003 or 2004. Deployment of up-looking FTS's in Brazil during this period would provide a unique and valuable opportunity for AIRS CO_2 product validation as well as information relevant for algorithm development for passive sensors. Aircraft CO_2 and O_2 overflights of the FTS might even be incorporated into the LBA airborne component. Leveraging off the LBA infrastructure and international agreements would substantially offset costs associated with deployment of the FTS.

A North American carbon budget experiment is being discussed by the IWG. Current plans have the experiment ending in ~2006. Airborne CO_2 sensors funded by the current IIP would come online in the 2004 timeframe and would add value to experiments based on COBRA that took place in July-August 2000 over the US. Airborne sensors developed in response to a proposed GCCP IIP-like program starting in 2003 would be ready for deployment in 2005-2006, so there may be an opportunity for combining an intercomparison among these instruments and with in situ sensors with the goals of the North American experiment. If a satellite CO_2 instrument is funded by the current ESSP, the earliest those data would be available is 2006 (assuming launch in 2005). Calibration and validation activities could potentially augment or extend the North American campaign.

A need for process studies in the Southern Hemisphere was identified and could possibly be combined with calibration and validation activities for future satellite missions in the post-2005 timeframe.

Issues that remain to be addressed:

1) More work on identifying opportunities for interagency collaboration and critical dependencies.
2) Refine definition and scope of modeling activities:
   - Identify issues that limit accuracy (resolution, inadequate knowledge of processes, CPU time).
   - Identify current and planned efforts to address these issues.
3) Catalog projected international efforts.
4) Interdisciplinary connections and critical dependencies.
5) Performance metrics.

Land (Workshop 2)

J. Collatz (chair), J. Masek and R. Knox (rapporteurs)

Attendees: D. Wickland A. England S. Ustin

J. Randerson	D. Skole	C. Potter
J. Luvall	B. Stokes	M. Buford
R. Hinkle	R. Dahlman	F. Hall
J. Gervin	P. Caruso	C. Tucker

As with the atmosphere and ocean, Land met in two breakout sessions. The sessions were devoted to discussions of the "technology wedge", (i.e. a set of activity blocks and timings that would lead to the new observational established during workshop #1) and discussions focused on the "science wedge" (i.e. the set of activities and timings that would utilize current space assets and capabilities to address the GCCP objectives and research goals defined in workshop #1). The Land Group met with oceans and atmospheres in a final plenary group to discuss GCCP deliverables and associated performance metrics.

The Land breakout discussions led to an initial definition of a technology and science architecture (activities, timing, output products) in support of the goals of the GCCP that can be costed prior to the third workshop. The discussion sessions were limited by a dearth of science and technological expertise on certain important topics, thus a number of issues still need to be resolved. Since some topics were not covered adequately during the workshop we have attempted to fill in some of the missing pieces in order to get the Science Working Group's and Carbon Cycle Steering Committee's response before the next step in the process. For the next workshop fuller participation by both remote sensing experts and discipline investigators will be sought.

High priority output products from the GCCP land effort discussed in the final plenary on deliverables and associated performance metrics include:

1) Global data sets of land cover type, biophysical parameters, biomass, disturbance and recovery (both coarse and fine resolution), and primary productivity
2) Synthesized sets of global observations (remote sensing and conventional data) needed to address the GCCP objectives and research goals,
3) New analysis tools (e.g. process and coupled models) to more effectively utilize remote sensing and conventional observations and
4) "Value-added" output products for the science community and stake-holders

A timetable for achieving results was proposed that initially exploits existing space assets (e.g. Terra, SeaWiFS, Landsat, AVHRR) and proceeds in the intermediate term to incorporate data from planned missions and ultimately aims at supporting new carbon cycle focused missions at the end of the decade.

1) By 2005 develop improved land cover algorithms that are more automated and use multiple sensors to extend our observational capability over more biomes, disturbance types and biomass ranges.
2) By 2009 develop new space based observational capability that can embrace the full range of global biomes needed for global assessments.
3) In 2002 begin preparations for and support an interagency North American Field Campaign (~2004)

A number of activities to be costed have been identified in each observational, technological and science category. Part of the process of putting together and costing an integrated GCCP will be to look for overlaps and synergies between the various activities that

will allow us to combine elements such as calibration/validation, model development/intercomparisons and in situ process studies. We must also consider coordinating these GCCP activities with existing or planned programs within NASA and other agencies.
At this point, we should make the following caveats. First, in this initial report, we include all activities that could ultimately represent NASA's contributions towards a complete global carbon inventory system. Secondly, the activities have not been evaluated for costs, or prioritized to produce a carbon cycle research program that responds to realistic resource constraints or desired timing. This can only occur in the context of both the atmosphere and ocean requirements and a definition of available resources. When all reports are available, the GCCP team (Science Working Group, Carbon Cycle Steering Committee, NASA HQ) must prioritize all activities, and produce resource requirements that are consistent with available resource levels.

Technology Development

Land cover data products

Land-cover refers to the categorical or quantitative description of what occupies the Earth's land surface. Categorical representations of land-cover in terms of fixed classes ("deciduous broadleaf forest", "wooded grassland") are being supplemented with continuous fields definitions, which unmix land-cover into endmember percentages ("80% woody material"). Land-cover acts as a critical input into carbon assessments in at least five ways:

1) biomass may be estimated from land-cover type using a lookup table approach.
2) land-cover change and disturbance events may be converted to estimates of biomass change (and hence carbon release) via a similar approach.
3) mapping regrowth as a separate class offers a way to estimate the area of forest recovery, and hence carbon sequestration following disturbance.
4) land-cover acts as a proxy for photosynthetic efficiency in many ecosystem productivity models.
5) accurate land cover classifications are needed to support new biomass measuring missions such as VCL

Technology and current assets

Technologies supporting identification and measurement of land-cover are relatively mature. Moderate-resolution multispectral passive optical sensors (Landsat, ASTER) permit fine-resolution mapping of land-cover parameters, and interannual to decadal comparisons to estimate land-cover change, disturbance, and disturbance recovery. Coarse resolution passive optical sensors (MODIS, AVHRR, SeaWiFS) permit the creation of dense spectral time series. These may in turn be related to variability of photosynthetic capacity (e.g. through fPAR) or may themselves be used to obtain land-cover classification. Both of these measurement approaches have continuity missions being planned for the next 10 years (Landsat Data Continuity Mission, NPP, NPOESS).

Both hyperspectral passive optical observations and low frequency active radar (SAR) offer some advantages over the traditional multispectral approaches. Hyperspectal offers improved discrimination of land-cover type. SAR allows repeated observations of high-latititude and tropical ecosystems, where cloud-cover and darkness may preclude acquisition of optical imagery. Hyperspatial measurement approaches (eg. SpaceImaging IKONOS data) are useful primarily as a source of calibration data.

Several processed data sets, useful for carbon studies, have already been derived from existing sources.

High Resolution:

- EarthSat/Science Data Purchase GeoCover Landsat TM/MSS product
- National Imagery and Mapping Agency (NIMA)-funded GeoCover global land-cover product
- Multi-Resolution Land Characterization-National Land Cover Data (MRLC-NLCD) 30-meter land-cover for United States
- NASA Humid Tropical Forest Inventory Project (Landsat Pathfinder)
- Global Rainforest Mapping Project (GRFM, NASDA) JERS-1 SAR mosaic

Coarse Resolution:

- IGBP DISCover AVHRR-based Land-cover data set
- University of Maryland (UMD) Global Land-cover data set and continuous fields
- AVHRR-Fourier-Adjusted, Solar zenith angle corrected, Interpolated Reconstructed (FASIR) 18 year (1981-1999) global biophysical parameter fields
- MODIS Land-cover/Continuous Fields/Land-cover change products

In addition, it seems likely that a year 2000 orthorectified global dataset from Landsat-7 ETM+ will be funded through NASA in coming months. These data sets provide raw materials for the generation of land-cover, biomass, and biomass change products before the launch of VCL or later missions. However, additional computational and algorithmic research is required to (a) process large volumes of global, multi-year Landsat data efficiently; and (b) extract specific classes related to disturbance (e.g. regrowth) on a global basis.

Beyond remote sensing measurement capabilities, several weaknesses or "gaps" in supporting technologies were noted. These included:

1) Lack of comprehensive training/validation suite for land-cover
   - Use field photos and IKONOS for numerous 1-time validation sites
   - Improved validation strategies for continuous fields variables
   - Assess scaling of land-cover via IKONOS-ETM+/MODIS studies
2) Need for automated techniques for analyzing global, multi-year Landsat data
3) Need for improved algorithms for mapping regrowth from passive optical data
4) Need for ancillary data to help with carbon accounting
   - National statistics on forest inventories, harvests
   - National allocations of forest harvest (lumber, paper, fuel, etc)

Proposed Activities

Initial land-cover/disturbance products and algorithm development

Global maps of ecosystem disturbance are given the highest priority. Disturbance was defined informally as a significant, transient change in biomass, and thus includes both anthropogenic causes (deforestation/harvesting, urban growth) and natural causes (fire, floods, insect damage). Disturbance maps should include the extent of disturbance, the time since disturbance, the type of disturbance and changes in disturbance frequency. In addition, a quantitative estimate of biomass loss during disturbance, and biomass gain during recovery, would be extremely useful. Ideally these assessments should be repeated every 2-4 years, to capture the exact timing of disturbance and map rapid regeneration in the tropics. The current

10-year snapshots provided by the Landsat GeoCover product were sufficient for an initial effort, however. In addition, land-cover type and land-cover biophysical variables (LAI, fPAR) are key inputs for ecosystem productivity models. The MODIS Land product suite provides one source for these parameters.

The following table translates the recommendations of the Land group into initial products, and gives a brief description of the analysis approach for each product. These products represent initial efforts, designed to improve information available to the land science community within the next 2-4 years, and will be improved by addition of future data sources (e.g. height information from lidar). In some cases (marked by italics), existing products may satisfy carbon science needs:

Table A5.1. Coarse Resolution (> 200 meter) products

Product	Input Data	Possible Analysis Approach
Land-cover Type	*MODIS*	*MODIS Land-Cover/LC Change*
Biophysics (LAI, fPAR)	*MODIS*	*MODIS LAI/fPAR product*
Biomass (1 km, 0.25 deg)	MODIS, in-situ observations from literature	Land-cover type to biomass lookup table
Biomass change (fast) (1 km, 0.25 deg/annual)	MODIS LC change, biomass estimates	Land-cover change to biomass change
Biomass change (slow) (1km, 0.25 deg / annual)	MODIS land-cover, LAI products	Interannual change in LAI coupled with land cover-biomass lookup tables

Table A5.2. Fine Resolution (< 200 meter) products

Product	Input Data	Possible Analysis Approach
Land-cover Type (1975, 1990, 2000 epochs)	Landsat GeoCover/2000	*NIMA classification*, supplemented by change detection; supervised classification
Biomass (1975, 1990, 2000)	Landsat land-cover, in-situ observations from literature, JERS-1 radar (?)	Land-cover type to biomass lookup table
Disturbance Type, Age (1990 – 2000)	Landsat GeoCover/2000, ASTER, in-situ observations/ field campaigns	Radiometric change detection, coupled with regional knowledge, spatial patterns, knowledge of regrowth rates.
Biomass change (fast) (1990 – 2000)	Landsat GeoCover/2000	Radiometric change detection coupled with land-cover derived biomass
Biomass change	Landsat GeoCover/2000	Radiometric change in vegetation

(slow) (1990 – 2000)		indices, coupled with regional knowledge, spatial patterns, knowledge of regrowth rates.

We propose to hold a workshop during summer 2001 in order to finalize the list of initial products and analysis approaches. We then anticipate an NRA during 2002 to divide production tasks among various researchers. Initial products should be completed in the 2004-2005 timeframe. Starting in 2004, we anticipate integrating lidar data (VCL) to improve these initial estimates of biomass and biomass change.

At the same time, we propose funding several groups to develop automated processing approaches for fine resolution land-cover data. These groups would concentrate on (i) improving production efficiency through advanced computing; and (ii) developing improved algorithms for extracting land-cover, disturbance, and biomass change information in an automated framework. This work may also include/require additional validation activities using hyperspatial satellite data and in situ observations. Thus, by the conclusion of these studies (~2005), the necessary technology and algorithms should be in place to generate routine, annual land-cover products for the globe (or for specific regions of interest) during 2005-2010. These annual, fine-cover assessments will reveal new information about the interannual variability of disturbance and biomass change, and how this variability correlates with climatic, ecosystem, and socioeconomic drivers. They will also directly address a main GCCP and USGCRP goal, namely, periodic reporting of the state of the global carbon cycle.

Disturbance: process understanding

A requirement for activities centered on studying the processes associated with disturbance was articulated at the workshop. The concept involves satellite missions that would focus on specific sites that were on the verge of or were recently disturbed. These selected sites would be observed from space at regular intervals with fine spatial resolution optical and thermal sensors. These measurements would be supported by in situ studies and site specific biogeochemical model development.

Existing assets such as Landsat-7 and ASTER may in part be able to meet the space based observational requirements for this activity. However, the future missions carrying fine spatial resolution thermal sensors capable of detecting the intensity of fires have not been identified.

Field studies and model development requirements proposed for this activity overlap and are included in activities associated with land cover/disturbance products described in the previous sections and biomass products described in the next sections.

Biomass and biomass change

New missions

Although initial biomass products will be developed from existing optical data sources (see section 1.1.1), these initial attempts will rely on "lookup table" approaches between land-cover and regional biomass, or on model outputs using land-cover inputs and are likely to be fairly crude. Further progress in refining global biomass and biomass change will require direct measurement of three-dimensional vegetation structure using new measurement approaches, culminating in a biomass-specific mission(s) in ~2009. This breakout was dedicated to exploring innovative remote sensing approaches for biomass.

Presentations reviewed existing remote measurement approaches for biomass and/or biomass change and a mission concept for characterizing ecosystem disturbance and regrowth. Assessing the associated technologies (see below) confirmed that a variety of applicable measurement approaches for biomass have progressed to airborne demonstrations. However, the most promising approaches for measuring biomass changes and differences among high-biomass forests were also the least advanced technologically. Intercomparisons of newer and more established approaches are needed to better define the biomass ranges and time-scales of change where each method could be expected to perform well on-orbit, and to develop synthesis methods for data fusion. All of the major approaches still need to be linked to one or more modeling frameworks that would propagate measurement performance/uncertainty to uncertainty in regional-to-global land-atmosphere carbon fluxes. Participants in the land-working group expressed skepticism about whether current process understanding and modeling capability could do so unambiguously. Although useful for mission formulation and mission concept intercomparison as a technology priority, a biomass carbon "OSSE" would be a lower scientific priority than effectively addressing the role(s) of disturbance in the terrestrial carbon cycle.

There was also a working group consensus that the requirements overlapped for potential missions to measure biomass, biomass change, and ecosystem disturbance. Biomass changes over a wide range of temporal and spatial scales, and includes responses to and recovery from disturbances and climatic signals. Disturbance includes both very rapid processes, such as fire and catastrophic windstorms, and more incremental changes from causes such as land-use intensification, acid deposition, introduced pests and pathogens, and human exclusion of fire. Some frequencies and scales of disturbance may also be accommodated within an ecosystem, without widespread changes in structure.

Table A5.3. Technology development status: Biomass/Biomass Change (1-5 Mg/ha)

Method	OSSE	In Situ & Ancillary	Airborne	Spaceborne
NIR Lidar (10-30m)	Needed (VCL using laser altimetry link models)	Commercial products (small spot); SERC/GSFC uplooking sensor)	Demo: LVIS; Commercial: small footprint, no waveforms; Needed: operational instrument	VCL (2003); SLA01 (flown), SLA02 (flown), SLA03 (2003)
Hyperspectral VNIR	Needed	Spectrometers Needed: hand-held imaging spectrometer	AVIRIS TRWIS-3 Hymap	EO-1/Hyperion (2000) Warfighter (2003)
Hyperspatial, Multispectral, Multitemporal	Needed	Commercial	Commercial	Commercial
Multiangular, Multipspectral (BRDF)	Needed	PARABOLA	AirMISR Vvarious others	MISR (1999) ALOS (2003) Biomass spatial resolution requirements?
P-band SAR (fully polarized)	Needed	Improved component allometric models; signature models for biomass	AirSAR	Needed
L-band SAR (quadpole)	Needed	"	Commercial	ALOS (2003)
InSAR	Needed	Models of scattering center height, as f(biomass)	Commercial	SRTM (2000, data-buy by 2002?);

				repeat pass InSAR (C, L band)
Dual-frequency VNIR lidar	Needed	Demonstration needed	Demonstration needed; calivration & validation options for other biomass missions	Needed
Data fusion	Needed	Modeling needed	More development needed	ALOS (2003) Envisat (2002)

To define requirements for new missions, types of biomass change can be grouped operationally by the associated rates of change in large-area carbon stocks. Requirements for a "disturbance" mission would focus on measuring synchronous rapid transfers among carbon pools over significant areas, whereas a second cluster of requirements relate to measuring rates of ecosystem response over longer time-scales.

Biomass mission development approach

As stated in Section1.1 Land Cover, we can take existing satellite land cover products, along with biomass data that already exists (much in the form of forest inventory data) and through literature-based vegetation type/age/biomass associations produce an initial global biomass map that will be useful for some initial carbon studies. Such an effort will also define more precisely the limitation in generating biomass maps with existing space assets. How well can biomass be estimated now in various ranges of biomass, and over what biomes? We will also gain experience in using these initial biomass maps which will help define future requirements.

In addition, the VCL, if launched in 2003, could provide useful information on canopy height and structure that when combined with allometry, and a knowledge of canopy type from the land cover maps, should result in significantly better biomass maps. A sensor fusion algorithm development effort is needed to combine the height information from VCL with existing land cover sensors such as ETM+, MODIS, MISR etc. to produce vegetation biomass and biomass change. However, the amount of global coverage obtained by VCL will depend directly on its orbital lifetime, currently budgeted for 12 months. VCL cloud-free data would cover most of the globe at least once at a one arc min. scale, but in order to observe biomass change directly, a follow on mission would be necessary.

It is clear that passive optical (both broad band and hyperspectral), lidar, radar, and BRDF sensors each provide some information for each of the biomass variables, but none definitively by themselves. So, this raises the question of strategy. Do we proceed with missions one at a time, or with combinations, and if so, which? Thus, we need to look at different measurement concepts, assess their capabilities, provide rough costs for each combination and make some assessment of how much of the land observational requirements would be addressed. Each of these instruments have been flown over boreal, temperate and tropical ecosystems. So, we might consider a data mining study. Or, if existing data is not adequate, it might be possible to collect some additional data with existing A/C ground instruments. We might also propose a series of a/c field campaigns using existing instruments focused on North. America, that is fly a/c versions over BOREAS sites, Pacific NW and eastern deciduous forests in 2003, 2004.

We are proposing therefore, a series of workshop beginning late this year to better define the Land requirements for the Land cover, Biomass/Biomass change and productivity variables and to define the 3-D trade space. The workshop series would conclude by the end of 2002 resulting in material to go into a solicitation requesting proposals for various measurement concepts.

Perhaps three to five would be selected at the beginning of 2003 for a pre-formulation study lasting one year. At the beginning of 2004 we would down select and begin bending tin for a 2008 launch.

Productivity

Productivity as defined in workshop discussions is the uptake of carbon by vegetation at time scales of minutes to years and is primarily driven by the physiological state of the vegetation and physical state of the climate and soil. Productivity defined in this way represents the uptake portion of the net carbon exchange. The actual net carbon exchange from a land surface is the difference between gross primary production and plant respiration, heterotrophic respiration, carbon emissions from fires and fossil fuel emissions. Imbalances between primary production (usually defined as either gross primary production (photosynthesis) or net primary production (photosynthesis minus plant respiration)) and carbon release via respiration, fires and fossil fuel emissions result in carbon sources or sinks. Thus primary production is only one component, albeit the important sink component of the land surface net carbon flux.
Other observational elements covered in the land break out sessions such as land cover, biomass and disturbance are functionally linked to productivity. Some examples of these links include:

1) Land cover characteristics are typically used to specify biophysical parameters in primary productivity models
2) Biomass increases are a result of the accumulation in living tissues of the products of primary productivity
3) Biomass can be used as a parameter in plant respiration models in the calculation of net primary productivity
4) Disturbance usually alters the composition and structure of the vegetation leading to changes in primary productivity

The GCCP will contribute improved information and understanding of the following components of primary productivity:

1) the absorption of photosynthetically active radiation (PAR) by the chlorophyll containing plant structures (expressed as a fraction of incoming PAR or fPAR)
2) the efficiency with which absorbed PAR is utilized to fix carbon from CO_2 (expressed as epsilon).
3) meteorological and soil conditions that control changes in fPAR and epsilon

fPAR is a function of the amount of green leaves, canopy structure and optical properties. Epsilon is influenced by the amount of soil nutrients available to photosynthesis and the physiological stress (water, temperature, pollution, etc) experienced by the vegetation.

Existing capabilities:
fPAR: Observations from various space-borne multi-spectral instruments at fine and coarse spatial resolution have been successfully used to estimate fPAR. The recently deployed Terra platform with the MODIS and MISR instruments are capable of producing highly useful improved estimates of fPAR. It is important that the GCCP foster the full utilization of these new data in carbon cycle models and ensure long term continuity in the availability of this type of data.

Epsilon: Currently, there are no routine estimates of epsilon derived from space platforms. There may be some capability for estimating chlorophyll content or water stress using the green band and water absorbing band respectively from MODIS. A number of promising techniques for estimating epsilon have been demonstrated using hyperspectral resolution data from helicopter and aircraft. The concept of using laser techniques to induce chlorophyll flouresence as a measure of photosynthetic activity has been proposed but as yet has not been demonstrated.

Ancillary: Several meteorological data assimilation models are providing forcing data to drive carbon cycle models. Specifically, NASA's DAO is producing meteorological products in support of the Terra mission. Also from Terra, the ASTER instrument will be providing topographic elevation data necessary for hydrological components of carbon cycle models.

New mission concepts/activities

The use of remote sensing for estimating primary productivity is either fairly mature and operational as in the case of fPAR or only at the concept level requiring further research and development before a space mission can be proposed. Below is a list of new technological approaches that may lead to improved estimation of primary productivity. In the cases of hyperspectral and multi-angle based concepts technological readiness is high but it is still necessary to demonstrate the usefulness/improvements these approaches provide for understanding and quantifying carbon fluxes. In other cases, such as fluorescence measurement techniques, the technological capability still needs to be demonstrated.

fPAR

1) Improved BRDF characterization of canopy structure using advanced multi-angle and multi-polarization approaches
2) Improved estimates of the green fraction of the canopy using multi-spectral lidar imaging
3) Hyperspectral approaches to characterizing the "red edge" between chlorophyll absorption and leaf near-infrared scattering

Epsilon

1) Hyperspectral approaches to estimating chlorophyll content of the photosynthetic portion of the canopy
2) Hyperspectral approaches to measuring acute physiological stress based on reflectance changes induced by the xanthophyll cycle
3) Passive emission measurements of steady state chlorophyll fluorescence
4) Active laser induced chlorophyll fluorescence measurements

Ancillary

1) Soil moisture
2) Improved precipitation measurements
3) Soil freeze/thaw state
4) Data assimilation modeling with improved meteorological accuracy and expanded to include more carbon cycle relevant data such as vegetation phenology and atmospheric CO_2 concentrations.
5) In situ, real time, trace gas and isotopic composition measurement technology development

Measurements of column and profile atmospheric CO_2 concentrations as proposed in the atmospheric break out group may be able to provide near direct measurements of productivity especially those approaches that can make measurements both in the day and night.

Activities to be costed

We propose that NASA continue to invest in the above listed instrument concepts and activities at least at a moderate level in order to capitalize on technological break-throughs and to demonstrate the usefulness of established technologies to answer carbon cycle questions. Some candidate approaches to improving primary productivity estimates that require further study are:

Hyperspectral approaches: In light of advances in data processing capabilities and instrument construction, hyperspectral approaches need to be re-evaluated in terms of the costs and data rate constraints that have limited the use of such approaches in the past. There is also a stated need for the development of an in situ imaging hyperspectral spectrometer for algorithm development and validation of aircraft and space borne imagers. Further field work is required that links hyperspectral measurements with carbon cycle processes studied in situ.

Multi-angle and polarization approaches: More advanced instruments following on MISR and other instruments of these types need to be demonstrated through instrument simulator aircraft measurements closely tied to in situ calibration/validation activities.

Laser-induced fluorescence: Work has been initiated by NASA to develop airborne laser techniques for measuring chlorophyll fluorescence of vegetation. However, scaling an aircraft instrument to a space platform faces several technological hurdles.

OSSEs: Determining Measurement Requirements

Discussions at the workshop highlighted our lack of knowledge about the spatial and temporal scales at which observations should be made in order to address the relevant science and management questions that we have identified. For instance, at what spatial resolution should space based observations be made that would be adequate to capture the carbon flux consequences of disturbance. For every observational requirement, be it some aspect of disturbance or biomass or productivity, the sampling and accuracy requirements are likely to differ. In addition, there are likely to be trade-offs between observation resolution/frequency and the precision of the observation itself, which may limit the utility of particular remote sensing approaches. In order to evaluate the strengths of each approach individually or in combination we need more information detailing how technical advantages propagate to reduce uncertainty within carbon flux models. The concept we propose to address these issues can be termed "Observing System Simulation Experiments" or OSSE which is derived from a concept used to develop observing systems for atmospheric properties. For land observations, the concept involves using biogeochemical and carbon accounting models to predict what scale of measurements and what accuracies are needed from a space observing system to achieve the science goals.

Simulation studies aimed at designing appropriate measurement technologies may be viewed as part of NASA's mission development process rather than as new science. This argument would support the proposal that NASA develop an in-house effort to coordinate the execution of land focused OSSE's for the development of new missions and other activities that

would provide products most useful to the science and stake-holder community. Such efforts would involve science teams from outside of NASA to provide models and scientific guidance. Each science product may have its own set of models and science team. Even the gross details of this kind of activity have not been considered but the benefits of quantitatively observatinal requirements to available technologies are obvious.

By the next workshop we will attempt to present a road map that establishes a mechanism for determining measurement requirements for new missions and activities. The activities will likely include further studies in the form of workshops and white papers to define the infrastructure needed to accomplish the OSSE approach for land. It is hoped that further guidance from our Science Working Group in the mean time will help us refine this requirement.

Calibration and Validation

Land cover

The working group advocated continued support for international land-cover validation campaigns. Existing efforts should be expanded to include several hundred sites, distributed globally, covering Earth's major biomes for the purpose of validating land-cover itself. The emphasis should be on providing an adequate sampling of spectral-temporal behavior of vegetation types to (i) validate existing land-cover products and understand sources of error; and (ii) provide a universally accessible source of training/validation data for future land-cover characterization efforts. Part of this effort may be satisfied by an IKONOS data buy.

Validating biophysical variables (fPAR, LAI, NDVI) is already a priority for the EOS program, and should be leveraged by the GCCP. Of particular importance are field campaigns, such as BigFoot, that combine multi-resolution land-cover characterization with flux tower measurements, to allow the "end-to-end" study of how variability in terrestrial vegetation affects net ecosystem exchange (NEE).

Biomass

To validate space-borne observations of biomass and biomass change, a global net work of sites would be essential. Such sites would augment calibration and validation activities conducted for the NA campaign. Collaborations with established programs such as the LTER program, FluxNet, Terra validation, the Tropical Forest Canopy Research program could significantly enhance the GCCP validation effort. These programs already have established long term sites where biomass, and biomass change are independently measured along with carbon fluxes in some cases. The development of ground based instruments to place at sites to obtain remote sensing measurements could support the development and validation of the various measurement concepts.

Productivity

A number of field measurement programs have already been conducted to develop and validate various techniques for vegetation productivity. Some of these programs, such as FIFE and BOREAS have produced CD-ROMS containing well-documented field measurements of hyperspectral reflectance, canopy optical and biological properties, carbon exchange, meteorological conditions, soils properties. However, these observations have largely concentrated on late regeneration and mature forests. Thus, there is a considerable gap in the field measurements of disturbance and recovery. Further, few measurements of flouresence using passive or active techniques have been conducted in conjunction with leaf physiology or

carbon exchange measurements. As a part of field campaigns (e.g. North American), basic measurements of this type would be necessary to develop productivity measurement concepts.

Field Experiments

The development of the new data products described in this report must include a significant field studies component, both to support of calibration/validation of remote sensing approaches, and to study biogeochemical processes relevant to carbon fluxes. Field work in support of GCCP objectives requires coordination between instrument development teams, science teams (measurement and modeling) and existing in situ measurement infrastructures.
The Interagency working group has articulated the need for a North American Field Campaign, and a planning workshop is scheduled in the 2001/ 2002 time frame. The NA Field Campaign is currently planned for the 2003 to 2006 time frame. The timing is right for the GCCP to benefit significantly from participation in such a campaign and the GCCP could in turn provide data products and analysis tools that would support the objectives of the campaign. From the land perspective, the involvement would focus on calibration and validation activities for the planned biomass/biomass change and fine-resolution land cover products as well as the development and validation of biogeochemical process models to use those observations. Existing ground or aircraft-based instruments (passive optical, lidar, radar, BRDF, polarimetric) instruments could be flown to explore and validate various measurement concepts and algorithms. In turn, these instruments, as well as existing space instruments, could contribute data products for use in scaling studies and biogeochemical flux analysis focusing on historical and current satellite-derived land cover. Data mining from past and ongoing field experiments such as FIFE, BOREAS and LBA could begin immediately and would contribute valuable data sets for measurement concept development and algorithm validation in the grasslands, boreal ecosystem and tropics. Future field activities in addition to the NA campaign would also contribute to further develop and validate land cover products, process models etc. A global net work of sites would also be valuable such as the LTER sites, the Tropical Forest Canopy Research sites etc, where biomass, and biomass change are independently measured, and where ground-based instruments could be mounted on towers and cranes for algorithm development and validation. In the boreal ecosystem, some limited campaign in Eurasia would be valuable in extending algorithms to this important geographic area. This could be in collaboration with European Union activities.

Particular attention should be paid to field studies that resolve below-ground biomass and soil carbon variability. These below-ground components, while not observable from remote sensing, constitute a major source of uncertainty in estimating NEE from remotely sensed observations of above-ground land-cover, biomass, biomass change, and productivity. The working group recommends that NASA work with other agencies to (a) continue field studies on estimating below-ground biomass and soil carbon; (b) support field studies that resolve sources of variability in these below-ground components, and (c) support development of new in-situ technologies for estimating below-ground components more accurately and efficiently.
Following the launch of new space capabilities in the post 2008 time frame, repeats of these experiments would be needed to support calibration and validation of the new sensors.

Modeling and Data Integration

The GCCP proposes to develop observations and model products as NASA's contributions toward quantifying, understanding and predicting carbon sources and sinks.

Developing useful products from space observations requires models of various types to convert raw signals into high level products. Since NASA is in the business of producing information from space observations, the Agency is responsible for fostering the development of models that utilize remote sensing data. Much work needs to be done to improve capabilities for merging different types of satellite and in situ data. A promising approach for merging disparate data into consistent and coherent products is data assimilation modeling which couples ocean and atmospheric as well as land data and processes. We propose to support such activities as part of the GCCP.

NASA as well as other agencies have a history of supporting the development and evaluation of global and regional land biogeochemical models. Some of these models utilize remote sensing data as inputs or for validation. Generally, these models account for disturbance in overly simplified ways or not at all. Improved data sets of land cover, disturbance and biomass derived from remote sensing products offer opportunities to improve the representation of management and disturbance processes in models. The generation of new data sets along with support for focused process studies and model development are activities that the GCCP proposes to augment beyond current capabilities.

Below is a list of modeling activities, some of which have been discussed in previous sections of this workshop summary, but are reiterated here for the purpose of consolidating the modeling requirements under one heading. The gross details of our modeling strategy were not well developed by the end of the workshop and are therefore more conceptual than definitive.

For land, the major groupings of modeling activities that need to be supported are:

1) Modeling the carbon consequences of land cover, management and disturbance
2) Modeling interannual variability and trends in primary productivity
3) Coupled land/ocean/atmosphere prognostic modeling

In support of modeling the following activities need to be developed:

1) improved remotely sensed inputs that characterize the state of the land surface
2) algorithm development and processing of data from existing sensors
3) production of improved data sets utilizing new data as they come on line
4) consolidation of existing in situ data from intensive long term field studies and inventory archives and merge with satellite data
5) focused process studies
6) model intercomparison activities
7) modeling to define measurement requirements and uncertainties

The above list is not specific because the details of such a plan require further focused input from the modeling community. A number of workshops and white papers are need to define:

1) science community data requirements - input data and validation information -what can we do with existing assets?
2) critically needed improvements in process understanding
3) model intercomparisions
4) measurement requirements for the development of new missions
5) user/stake holder data/product requirements

Activities that need to be costed

1) NRA directed at modeling of carbon flux consequences of disturbance, the utilization of new disturbance and biomass products generated from existing data, and the measurement requirements needed from new observations. This activity could also include model intercomparisons (~2002-2005)
2) Support for land model component within a NASA data assimilation system. This activity may include funding for core capabilities as well as for a support team of scientists from outside (~2003-2010).
3) Continued support for prognostic and assessment models being developed both by NASA and by the science/policy community.

Oceans (Workshop 2)

W. Gregg (chair), S. Signorini (rapporteur)

Attendees:	C. del Castillo	L. Dilling	R. Feely
	F. Hoge	J. Marra	J. Moisan
	T. Moisan	C. McClain	J. Christian

The Ocean Carbon Working Group (OCWG) met several times between Mar. 20 and 22, 2001, as part of the second GCCP workshop. The objectives at this workshop for the OCWG were:

1) Define the specific technological activities and potential remote sensing missions necessary to achieve the goals of the ocean component of the NASA GCCP
2) Define the specific science activities necessary to achieve these goals
3) Define timelines

The OCWG reiterated the 3 overarching scientific objectives for the GCCP.

1) What is the seasonal-interannual-interdecadal variability of ocean carbon fluxes at basin scales and sufficient to $\pm$ 0.1Pg C/yr
2) What controls the magnitude and variability of ocean carbon?
3) What are the scientific consequences of changes in the global carbon cycle on ocean carbon cycling processes?

The OCWG strongly recommended the formation of active calibration/validation activities under the auspices of the GCCP. This calibration and validation team would have 4 main responsibilities:

1) assess accuracy of derived carbon variables in the traditional manner of calibration and validation activities
2) assure seamless time series of derived carbon variables for long-term remote sensing observations – this is an activity that does not fall within the purview of individual missions, but is critical for understanding natural variability
3) provide estimate of errors and error length scales of carbon-related variables – this is important to characterize natural variability but also to support data assimilation
4) assure, adhere to, and develop standards for measurement, sampling, and handling of carbon-related variables – this assures consistent and accurate observations, and may be established through partnerships when possible

The calibration and validation team must be coordinated and comprehensive: it must sample ALL relevant variables simultaneously, and it must act in concert with simultaneous activities of the other disciplines, i.e., land and atmosphere, were appropriate.

The OCWG also supported the development of 1-3 field studies on US coasts where process experiments and remote sensing tests can be performed. Participation in formal field experiments such as those planned by NOAA in the North Atlantic and Pacific is desirable. A strong interagency collaboration with NOAA and planned routine field surveys is mandatory to provide routine in situ carbon information for model validation and assimilation and to support remote sensing and in situ technology development.

The OCWG reviewed a comprehensive list of specific scientific objectives that included information on a set of ocean, atmospheric and terrestrial variables that is necessary to meet the overarching objectives. There were 3 changes to the requirements list:

1) land-sea carbon transfer processes were added as a general program category to explicitly include coastal and river processes.

2) particulate organic carbon was added as a specific requirement because of its importance in the global carbon cycle and our objective of quantifying pCO_2, and because recent papers have suggested a possibility of evaluating it from spaceborne observations, making it relevant to the NASA GCCP,

3) bicarbonate was added to the requirements list because it dominates the inorganic portion of ocean carbon, and because there is potential for observing it from remote sensing (although feasibility studies will need to be carried out).

Technology Wedge

Methodologies to achieve ocean carbon objectives span literature review through proof-of-concept. A summary of key parameters and methodologies for the technology wedge is provided in bullet format below. The relationships between the various ocean physical and biogeochemical variables and rates are shown in Figure A5.1. Also, we have identified 9 potential new technologies:

1) brightness temperatures (salinity)
2) active fluorescence(taxonomy, photosyn., HCO_3)
3) passive fluorescence(taxonomy, biomass, photosynthesis)
4) UV (taxonomy, CDOM, nitrate)
5) NIR (taxonomy)
6) hyper or select-spectral (taxonomy, CDOM)
7) LIBS (Laser-Induced Breakdown Spectrometer) (total ocean C)
8) in situ instrument development (ancillary variables)
9) radar enhancement? (gas transfer coefficients)

Ocean Technology Wedge: Key Parameters and Methogologies

- **Ocean pCO_2**
- **Gas Exchange Coefficient (external help needed)**
  - Algorithms
  - In Situ Observations
  - Wave Tanks
  - SAR
  - Radar Missions

- Process Studies
- SST, SSS → Critical Dependency

- **Physical Forcing (to be obtained from available sources)**
  - Ocean Circulation
  - Ocean Mixed Layer Depth
  - Surface Irradiance
  - Sea Ice
- **Primary Production**
  - S-Active Fluorescence
  - Variable Fluorescence
  - Passive Fluorescence
  - UV – Amino Acids
- **Dissolved Organic Carbon (DOC)**
  - UV
  - Field Experiments
  - Calibration Technologies
  - Atmospheric Correction
- **Biomass**
  - Active Fluorescence
  - Field Experiments
  - Aircraft
  - Passive Fluorescence

A5.3. Workshop 3 (May 2 - 4, 2001)

Atmospheres (Workshop 3)

R. Kawa (chair), A. Andrews (rapporteur)

Attendees:	S. Denning	R. Chatfield	J. Abshire
	J. Burris	F. Murcray	W. Heaps
	S. Pawson	R. Engelen	A. Aiken
	C. Barnet	D. Crisp	L. McMillin
	H. Singh	C. Miller	S. Wofsy
	S. Ismail	E. Browel	R. Barne
	M. Suarez	P. Tans	R. Salawitch
	R. Menzies		

Break-out Session #1

Discussion opened with an overview of the strategy for getting spaceborne CO_2 measurements and inferring fluxes that was established at the previous two workshops. Attention then turned to a review of the draft schedule of activities posed by the GCCP development team following Workshop 2. Planned and existing space missions were summarized to set the framework for proposed GCCP activities (chart needs lifetimes for existing missions).

Brief discussion concluded that SCIAMACHY may yield some useful information on CO_2, but precision and spatial resolution will limit applicability to carbon problems. TES will also provide extensive tropospheric chemistry information including CO, CH_4, and some organics (although organics will not be primary products). The comment was raised again from

the morning session that CH_4 + volatile organic compounds (VOCs) make the same order of magnitude contribution to the C budget as CO_2 imbalance (~1% of CO_2). Thus, the GCCP is not just CO_2. CO also helps disaggregate fossil fuel contribution from other sources. HCN may be an additional useful tracer for biomass burning.

The possibility of CO_2 sondes was discussed. The objective would be to enable frequent CO_2 profiling with high precision but at low cost. The difficulty of intercalibration of such sensors would likely lead to prohibitively large expense. Systematic errors in the observations are a very serious problem for inferring fluxes since any calibration bias will be interpreted and integrated as a source or sink. One estimate is that bias must be eliminated at the level of 0.1 ppmv.

Strategies for deployment of additional ground-based remote sensors and analysis of data for CO_2 were discussed at some length. These measurements have high value for calibration and validation of space instruments as well as independent value for inferring sources and sinks when used with the existing surface network. They should be collocated with the surface sites where possible. Location at ARM/CART sites would allow integration of CO_2 data with measurement of cloud and other radiation parameters. Measurements across a range of latitudes would be desirable to simulate space sampling. Data across longitude over land would also be useful to look for flux divergence. First attempts should be at sites with simple topography to simplify interpretation and comparison to surface data.

Continuing discussion from Workshop 2, data from the historical record of up-looking spectrometers was discussed. Data from the Network for Detection of Stratospheric Change (NDSC) is a good source, although many of these sites are at high altitudes to avoid low-level variations, which are the target of CO_2 measurements. Wide spectral coverage of these instruments provides many constituents, CO, CH_4, N_2O, O_2, etc. and the record contains a lot of temporal information. NDSC spectra are generally available from the individual investigators, but spectra are not in archive since the files are too large (~100MB/day). One needs to be cautious of changes in station operation affecting the data. Raw data are available and need to be analyzed in standard method. This is current NDSC procedure so mechanisms are in place that CO_2 analysis could fit into. It appears unlikely that NOAA would fund network augmentation. High accuracy for these data is needed to avoid bias.

The need for improved lab spectroscopy on CO_2, CO, and CH_4 was identified in order to attain highly precise and accurate remote sensing measurements. Note that there are no new initiatives for CO and CH_4 planned in the GCCP. The merits of MOPITT and TES data for CO and CH_4 were discussed. Data quality has to be established. The need and/or benefits of collocated CO and CH_4 for source/sink partitioning will be explored in measurement impact studies. Although no instrument development for CO and CH_4 is planned, learning to measure CO_2 to < 1% will inform methods for other species.

Discussion of field campaign activities identified that AIRS validation is missing. The North American carbon budget experiment will provide an opportunity for validation of both Aqua and Aura under current schedule. In general the measurement activities outlined on the chart were accepted as appropriate and largely complete.

Continuing discussion focused on modeling activities. Confusion on the definition of what is included in an OSSE led to a need to identify component model and algorithm development more specifically. The question was discussed as to whether observational system simulations should continue to be done by individual groups or if a central facility with standard tests should be provided by the GCCP. A significant expense for GCCP computing was noted.

Discussion was deferred to plenary. Modeling activity chart was generally thought to need better description, organization, and intermediate milestones/accomplishments.

A first presentation of budgeting associated with modeling activities provoked much discussion. It was generally agreed that the modeling activities needed to be better motivated and connected to the overall science objectives of the GCCP. Several approaches for doing so were suggested. Atmospheric modeling cannot be planned without integrating other disciplines. One suggestion was to focus on 2 objectives: inversion modeling for sources /sinks and climate prediction. Lack of a role for regional scale models was questioned in such an approach. Clearer big picture, crystallized questions, centralized objectives, hypothesis testing, and critical dependencies need to be fleshed out. Sub-group on modeling objectives may be needed. We need models to connect concentration measurements to fluxes, but how much improvement is needed, what spatial and temporal resolution, what processes? What role does assimilation play?

Breakout Session #2

A draft budget was distributed for participants to review and comment on later in the workshop. The primary topic of discussion was to revisit the issue from yesterday: connecting goals to activity blocks. A draft conceptual framework was presented. The logic followed from the first two USGCRP Goals (as applied to the atmospheres discipline), to inferring carbon fluxes, to the need for CO_2 measurements and models, to the GCCP activities. A draft roadmap of activities for the GCCP was presented. This draft framework was generally considered an appropriate way to connect the activities. It needs to be made presentable.

The role of assimilation was discussed. Assimilation provides one method to infer fluxes at high temporal and spatial resolution. The merits of using assimilation to produce a full global CO_2 time series from various observations were debated. The users of such a field and their requirements need to be determined. Comparison with independent data is an important way of evaluating the model and data consistency. Field campaigns need data on multiple scales. Interactions and comparisons with oceans and lands are needed to give best estimates as well as uncertainties. It is still important to consider separate elements to get the underlying models correct. Note that a variation in atmospheric CO_2 concentration over ocean is a minor source of uncertainty in calculating air-sea flux, so highly resolved field is not necessary.

A concern was raised that space mission technology development was not included in the budget for mission activities, which was presented in plenary, nor was it picked up in the atmosphere budget draft. This issue was raised again in the plenary.

A question was raised about remote sensors that do not have a pathway to space, but that might work from aircraft. These sorts of instruments could be motivated by validation needs and will be considered along with in situ sensors. Discussion concluded with further thoughts on GCCP scope. Direct relevance to CO_2 interpretation and modeling is the standard that limits GCCP involvement.

Land (Workshop 3)

J. Collatz (chair), J. Masek (rapporteur)

Attendees:	M. Cao	W. Cohen	R. Dahlman
	G. Gutman	F. Hall	R. Hinkle
	S. Houghton	E. Kasischke	J. Kimball
	R. Knox	R. Miller	R. Myneni
	S. Saatchi	S. Ustin	D. Wickland

Discussions during Plenary

Thus far, the GCCP and for that matter the USGCRP CCIWG and the US Carbon Cycle Science Plan have emphasized the CO_2 budget of the atmosphere. What about other carbon species such as VOC, CO and CH_4? Though the science community has generally pushed the emphasis on CO_2, the activities of the Land component of the GCCP involving biomass, land cover, disturbance measurements will contribute towards understanding of CO emissions from biomass burning and CH_4 emissions from wet lands and biomass burning. A question arose on the dependence of the GCCP on the success of measurements of CO_2 from space. Even without such measurements the proposed Land missions would contribute much to reducing uncertainties in the carbon budget and are justifiable. While the proposed missions among the disciplines are not necessarily dependent on one another, the science activities have to be integrated among all disciplines.

Also discussed was the relationship between land science products and the needs of the atmospheric modeling efforts. For example, how do biomass and biomass change as we plan to estimate them relate to the CO_2 budget of the atmosphere and the proposed NACP? Land and atmospheres discipline activities must be highly coordinated around addressing the same over-arching science questions and goals. It seems that OSSEs that couple land and atmospheric processes is one avenue for maintaining coordination.

Land Breakout Sessions Report

Though landcover observations are needed and contribute directly to the other identified observational requirements (disturbance, biomass change, productivity), it was argued strongly by some that landcover should be included as a separate observational requirement. Given we can already make useful measurements of landcover, disturbance regime and productivity, the new capability that we need to emphasize in the land component of the GCCP is measurement of biomass and biomass change. It was argued by some that the GCCP should not explicitly include biomass as a derived product from existing sensors (land cover products) because:
(a) if we say we can already measure biomass how do we build a strong case for developing new missions?
(b) we can only do it poorly now using traditional land cover products.

Initial Land Cover Products
Costed Activities

1) Workshops in 2002 to define processing methodologies, data sources and organizational approaches
2) 2003-2005 - Manual processing of Landsat from '70s, '80s, '90s and 2000 to produce land cover and land cover change products. Include support for science and algorithm development
3) 2003-2005 - Develop and implement automated processing system utilizing Landsat-7
4) 2006-2011 Automated processing of Landsat follow-on merged with other data sources including new biomass missions. Also must include science, algorithm development and calibration and validation studies in support of products.
5) Resources to contribute to the development of a global biomass database assembled from archives and inventories (in situ estimates) and provide support through NRA's for the utilization of the new landcover products by the science community to study carbon

sources/sinks associated with landcover type and landcover change. Activities to develop initial landcover products should not just emphasize Landsat, but merge other satellite data as well, especially MODIS and MISR. Activities should also involve other international efforts to derive specific regional and land cover type products. By coordinating with these efforts and sharing of data, costs may be brought down. Also, rather than wall to wall processing for specific epochs, certain regions may require more frequent analysis of change, and others less frequent analyses . Decide the time scale on a per region basis.

New Biomass Missions

Costed Activities

1) Workshops in 2002 to define observational requirements, review existing information and develop approach for intercomparison and evaluation of proposed methods.
2) 2003-2005 - Airborne field campaigns for demonstration and intercomparison of remote sensing methods for measuring biomass and biomass change. Some of these efforts will be part of the NASA contributions to an interagency NACP.
3) Based on results of workshops and intercomparisons, Announcements of Opportunity for a Biomass Mission should be released and mission formulation activities will proceed.
4) Demonstration and calibration and validation efforts need strong in situ component of biomass and soil carbon measurements as well as analysis of archival data.
5) Some airborne biomass studies have already been completed and further analyses and comparisons of these data need to be pursued.
6) In situ observations of biomass and soil carbon in support of airborne demo activities should also be coordinated with concurrent space missions such as VCL, ALOS, GLAS, (others?).
7) Given these extra requirements, it was felt that the budget allocations to airborne/space biomass measurement demo and calibration and validation activities should be increased.

New Productivity Missions

Space assets are already in place that have capabilities to estimate productivity using multispectral and multiangle optical measurements to obtain absorbed PAR. It may be possible to measure the efficiency of PAR utilization via hyperspectral and/or fluorescence (active, passive) approaches. It was proposed that NASA continue to explore fluorescence measurement technology at a moderate level in case technological hurtles are overcome. The contributions of hyperspectral techniques to estimation of productivity could be evaluated as part of or extension of activities involving hyperspectral measurement of landcover, disturbance state and biomass. Initially workshops would be convened to determine appropriate needs and actions for improving productivity measurements.

Disturbance Processes Mission

A workshop in 2002 should be held to consider/reconsider existing and planned activities for studying disturbance processes using space borne sensors. One outcome could be a proposed mission such as the vegetation recovery mission or as proposed by Ames.

OSSE Modeling

The GSFC team proposed that a modest continuing effort be supported to define measurement requirements and other uncertainties using biogeochemical models linked to atmospheric tracer modeling (and atmospheric OSSEs).

Field Campaigns

1) Workshops in 2002 to define elements of NASA's land component of the NACP. The GSFC team proposed that the NACP would consist of two intensive years separated by a year of lower level monitoring and evaluation of previously collected data. The GCCP land component would support ~30 teams to do process modeling, process measurements and remote sensing calibration and validation as well as provide infrastructure support. Additional resources would be required to support airborne measurements for intercomparisons and demonstrations of biomass remote sensing techniques.
2) An additional extensive field campaign perhaps in Eurasia or tropics is proposed to be mounted near the end of the NACP at approximately half the level of support for the latter.
3) It was also pointed out that other internationally supported field campaigns are ongoing or planned in areas such as Africa and Southeast Asia and that the GCCP should identify where, when and how its resources could augment these studies in order to achieve our science goals involving the global perspective.

Data Synthesis

It was proposed by the GSFC planning team that with science community input (workshops) the land component of the GCCP would include a modest contribution to a larger effort to provide the infrastructure for distributing carbon and ancillary data products to the science community throughout the duration of the GCCP.

Other Science Investigations

The GSFC planning team recommended a modest level of support for integrating biogeochemical models into coupled land/ocean/atmosphere models as part of a larger model integration effort. This effort was envisioned to deal with prognostic earth system modeling in contrast to data assimilation modeling which also requires coupled models, but is considered elsewhere in the GCCP.

Other Issues discussed in Land Break out sessions:

1) Mechanics and strategy for developing the GCCP presentation for NASA HQ
2) Contributions of biomass measurements to the NACP. Long term regional sinks for carbon are likely to be slow processes involving among other things regrowth or aforestation, processes that are not likely to be observable during relatively short duration field campaigns. What is the relationship between an aircraft flux measurement and land use contributions to net carbon fluxes? Certainly land cover products will help identify the relationships between various land cover states and the fluxes of carbon associated with them. In addition, one of the goals of the NACP as stated in Steve Wofsy's plenary talk is to establish a legacy of observations and infrastructure to carry forward in subsequent years. The GCCP biomass and land cover characterization during the campaigns would contribute to the baseline for continued monitoring.

Oceans (Workshop 3)

W. Gregg (chair), S. Signorini (rapporteur)

Attendees:	M. Behrenfeld	N. Blough	M.-E. Carr
	J. Campbell	P. Caruso	C. del Castillo
	A. Chekalyuk	J. Christian	M. Cleave
	R. Feely	I. Fung	J. Goes
	F. Hoge	S. Hooker	C. McClain
	J. Moisan	T. Moisan	O. Spaulding
	D. Vandermark	R. Wanninkhof	J. Yoder

The objectives at this workshop for the OCWG were to review the ocean carbon plan, activities, and budget.

Rik Wannikof presented an overview of the state of research in air-sea exchange, how SOLAS is approaching the problem, and how the GCCP might help. His suggestions on the GCCP ocean plan were the following:

1) The air-sea exchange plan is inadequate and under-funded.
2) The plan requires a sea surface roughness-to-gas exchange algorithm.
3) The program needs to link funded investigations.
4) The plan needs 4-5 additional investigations to develop the algorithms.
5) $500-1000K is required for instrumentation and field data collection.

Dick Feely and Wanninkhof suggested that more emphasis be placed by the GCCP on ocean color-to-pCO_2 relationships, utilizing data synthesis (SST, SSS), algorithms, and in situ technology development and sampling (2-5 additional investigations)

There are breakthrough technologies emerging for in situ observations of carbon and carbon-related variables in the oceans. Inez Fung presented recent results from the Jim Bishop's drifter, which measures particulate organic beneath the surface and can be surfaced to correlate observations with satellite overpasses. Dick Feely discussed the Liquid Core Wave Guide technology, developed by R, Byrne (University of South Florida), which can measure in situ properties very important and relevant to NASA, including pH, 3 DIC components, nitrate, silicate, iron, phosphate, and ammonium. These breakthrough technologies are important to the GCCP. Development, testing, and sea validation are relevant to the program. Omar Spaulding (NASA SBIR Program Manager for Code Y) indicated that novel demonstration programs to collect data, innovative uses of satellite communications, and field experiment support are all valid NASA concerns and relevant for NASA funding.

Joaquim Goes presented a description of a field sampling program in the Gulf of Maine that has relevance to the GCCP, and the group desired more explicit links with such programs and an active search of further collaboration with other such programs.

Tiffany Moisan presented a comprehensive list of required variables to be sampled during the coastal field sampling experiments proposed by the ocean carbon working group. The list was considered exhaustive and sufficiently developed to enable costing, but may require refinement of strategy.

The group reviewed the importance of studying CH_4, given the suggestion earlier in the plenary session. The consensus was that is was of minor importance in global oceans (1% of total CH_4 budget). Although there was dissent, it was based on our considerable lack of

knowledge about the issue. In a 10-year program, such as the GCCP, course corrections can be undertaken if new results come to light and suggest pursuing this area of research.

Chemical species and detection limits of the Liquid Core Wave Guide (LCWG). Information provided by John Moisan.

Chemical Species	LCWG detection limit (with a 5m guide)
NH	0.50 nmol
NO_2	0.22 nmol
NO_3	0.22 nmol
PO_4	0.44 nmol
Fe_2	0.36 nmol
Mn^{2+}	0.89 nmol
Cu^{2+}	0.62 nmol
Zn^{2+}	0.36 nmol
Cd^{2+}	0.31 nmol
Ni^{2+}	0.16 nmol

It has also been used to measure pH with a precision of the order of +/- 0.0005 pH units. A system is in development to measure pCO_2.

APPENDIX 6. WORKSHOP ATTENDANCE LIST

	Workshop 1	Workshop 2	Workshop 3
Abshire, Jim/NASA GSFC	X		X
Adamec, David/NASA GSFC	X		X
Aikin, Arthur/NASA GSFC			X
Andrews, Arlyn/NASA GSFC	X	X	X
Arzayus, Krisa/NOAA		X	
Azerbarjin, Art/NASA GSFC	X		
Bacmeister, Julio/NASA GSFC	X	X	
Barnes, Bob/NASA GSFC			X
Barnes, James/NASA LaRC			X
Barnet, Chris/NASA GSFC	X	X	X
Behrenfeld, Mike/NASA GSFC	X	X	X
Bhartia, P.K./NASA GSFC	X		
Blough, Neal/University of Maryland			X
Browell, Ed/NASA LaRC	X		X
Buford, Marilyn/USDA		X	
Burris, John/NASA GSFC			X
Campbell, Janet/University of New Hampshire			X
Cao, Mingkui/University of Maryland			X

Carr, Mary-Elena/NASA JPL	X		X
Caruso, Paul/NASA GSFC	X	X	X
Chatfield, Bob/NASA HQ	X	X	X
Chekalyuk, Alex/NASA WFF		X	X
Christian, Jim/NASA GSFC		X	X
Cleave, Mary/NASA HQ		X	X
Cohen, Warren/USDA			X
Collatz, Jim/NASA GSFC	X	X	X
Crisp, David/NASA JPL		X	X
Dahlman, Roger/DOE	X	X	X
del Castillo, Carlos/NASA SSC	X	X	X
DeMaio, Lou/NASA GSFC	X	X	X
Denning, Scott/Colorado State University	X		X
Dilling, Lisa/NOAA	X	X	X
Engelen, Richard/Colorado State University		X	X
England, Tony/University of Michigan	X	X	
Esaias, Wayne/NASA GSFC			X
Falkowski, Paul/Rutgers	X		
Fargion, Giulietta/NASA GSFC	X		
Feely, Dick/NOAA	X	X	X
Field, Chris/Carnegie Institute	X		
Fung, Inez/UC Berkeley	X	X	X
Gervin, Jan/NASA GSFC	X	X	X
Goes, Joachuim/Bigelow Laboratory			X
Goldberg, Mitch/NOAA	X		
Gregg, Watson/NASA GSFC	X	X	X
Gutman, Garik/NASA HQ			X
Hall, Forrest/NASA GSFC	X	X	X
Habib, Shahid/NASA GSFC	X		
Heaps, Bill/NASAGSFC			X
Hinkle, Ross/NASA KSC	X	X	X
Hoge, Frank/NASA WFF		X	X
Hooker, Stan/NASA GSFC			X
Horrigan, Sarah/OMB	X		
Houghton, Richard/Woods Hole Ocean. Inst.			X
Houser, Paul/NASA GSFC	X		
Ismail, Syed/NASA LaRC		X	X
Jawson, Michael/USDA	X		
Kasischke, Eric/University of Maryland			X
Kawa, Randy/NASA GSFC	X		X
Kaye, Jack/NASA HQ	X	X	
Kimball, John/University of Montana			X
Knox, Bob/NASA GSFC		X	X
Luvall, Jeff/NASA MSFC		X	X
Marra, John/NASA HQS	X	X	
Masek, Jeff/NASA GSFC		X	X

McClain, Chuck/NASA GSFC	X	X	X
McMillin, Larry/NOAA	X	X	X
Menzies, Robert/NASA JPL			X
Miller, Charles/NASA JPL		X	X
Miller, Richard/NASA SSC	X		X
Mitchell, Karen/NASA GSFC	X	X	X
Moisan, John/NASA WFF	X	X	X
Moisan, Tiffany/NASA WFF	X	X	X
Moore, J. Keith/UCAR	X	X	
Murcray, Frank/University of Denver			X
Myneni, Ranga/Boston University			X
Pawson, Steve/NASA GSFC	X	X	X
Penner, Joyce/University of Michigan	X		
Potter, Chris/NASA ARC		X	
Randerson, Jim/California Institute of Technology		X	
Ranson, Jon/NASA GSFC	X		
Rienecker, Michele/NASA GSFC	X		
Rummel, John/NASA HQ	X		
Saatchi, Sasan/NASA JPL	X		X
Salawitch, Ross/NASA JPL	X		X
Sheffner, Ed/NASA HQ		X	
Signorini, Sergio/NASA GSFC	X	X	X
Singh, Hanwant/NASA ARC			X
Skole, David/Michigan State University	X	X	
Spaulding, Omar/NASA HQ			X
Stewart, Richard/NASA GSFC			X
Stokes, Bryce/USFS		X	
Strow, Larrabee/University of Maryland		X	
Suarez, Max/NASA GSFC	X	X	X
Susskind, Joel/NASA GSFC	X		
Tans, Pieter/NOAA			X
Trumbore, Susan/UC Irvine	X		
Tucker, Jim/NASA GSFC	X	X	
Ustin, Susan/UC Davis	X	X	X
Vandermark, Doug/NASA WFF			X
Wanninkhof, Rik/NOAA			X
Weir, Trisha/NASA GSFC	X		X
Wickland, Diane/NASA HQ	X	X	X
Wofsy, Steve/Harvard University	X		X
Yoder, Jim/University of Rhode Island	X		X

Appendix 7: Global Carbon Cycle Presentation

Presentation to NASA Headquarters

June 18, 2001

Dr. Scott Denning

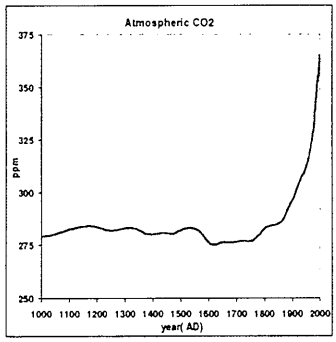
Dr. Forrest Hall

On behalf of the NASA carbon cycle formulation team

National Academy of Sciences 2001 Report

- "Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise."
- "Temperatures are, in fact, rising."

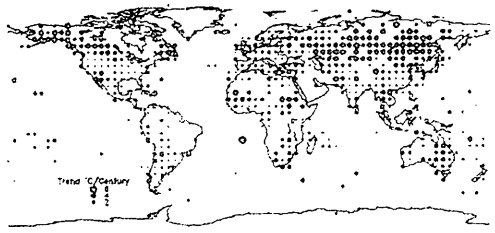
Greenhouse Gases and Warming



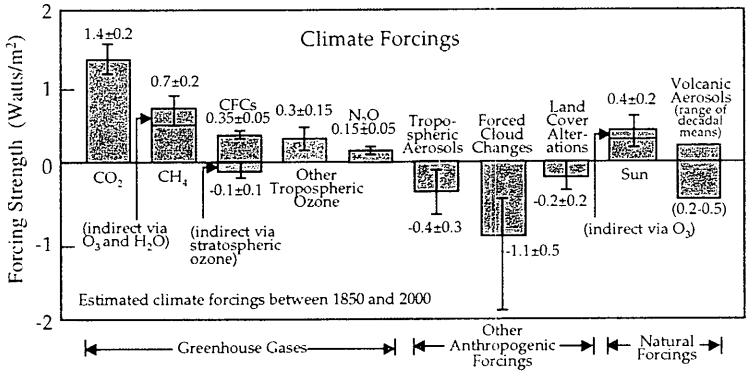
A major contributor to climate warming is the steady increase in atmospheric greenhouse gases.

Weather station records and ship-based observations indicate that global mean surface air temperature warmed between about 0.4 and 0.8 °C (0.7 and 1.5 °F) during the 20th century.

Trends of surface temperature (1951–1993)
Global Historical Climate Network (GHCN)

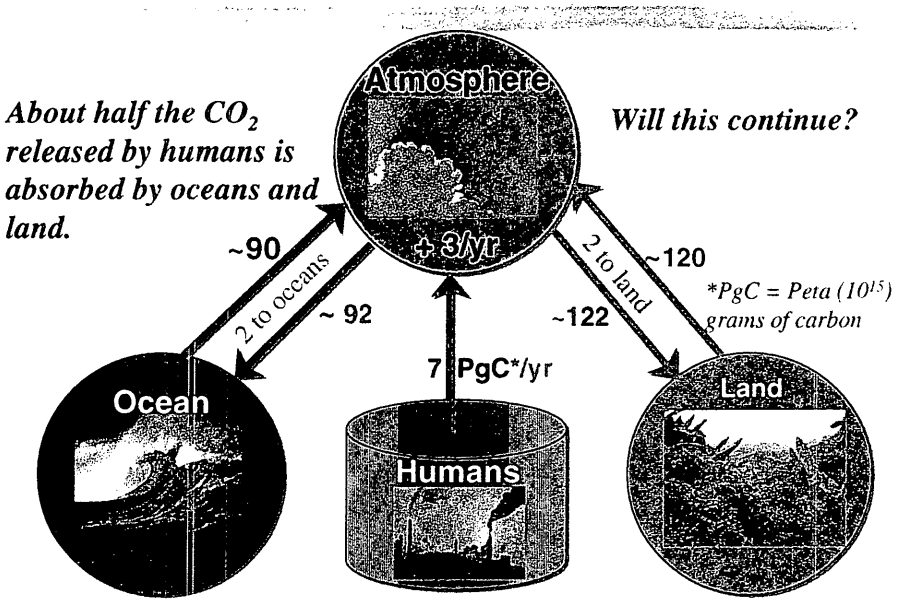


Climate Forcing Factors



Climate warming from 1850 to 2000 resulted from both human activities and natural causes.
Carbon dioxide played an important role.

The Global Carbon Cycle



Where Has All the Carbon Gone?

- Into the oceans
  - Solubility pump
  - Biological pump
- Into the land
  - CO_2 Fertilization
  - Nutrient fertilization
  - Forest regrowth, fire suppression, woody encroachment, etc.
  - Response to changing climate

What happens next?

"How land contributes, by location and processes, to exchanges of carbon with the atmosphere is still highly uncertain. . . ."

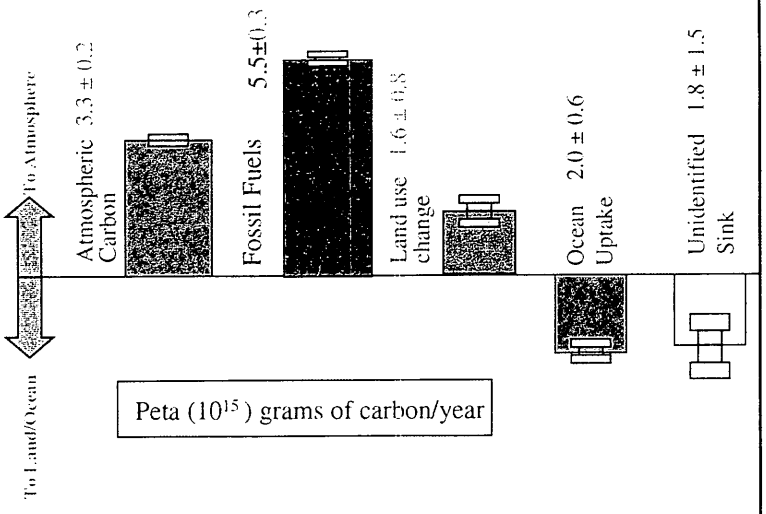
"These estimates [of future carbon dioxide climate forcings] . . . are only approximate because of uncertainty about how efficiently the ocean and terrestrial biosphere will sequester atmospheric CO_2."

National Academy of Science, 2001

Current Uncertainties

Current source and sink strengths are uncertain.

Prediction of future climate forcing is therefore uncertain as well.

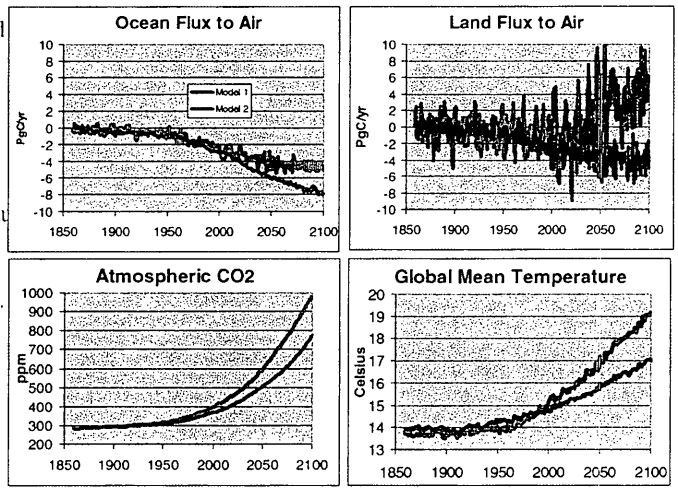


Uncertain Futures

As CO_2 emissions have increased, the land and oceans have absorbed more and more carbon

Projections of future CO_2 levels depend on ou knowledge of the biosphere and how it interacts with climate.

Given identical human emissions, different models project dramatically different futures



Which is correct? How can we know?

Potential Consequences

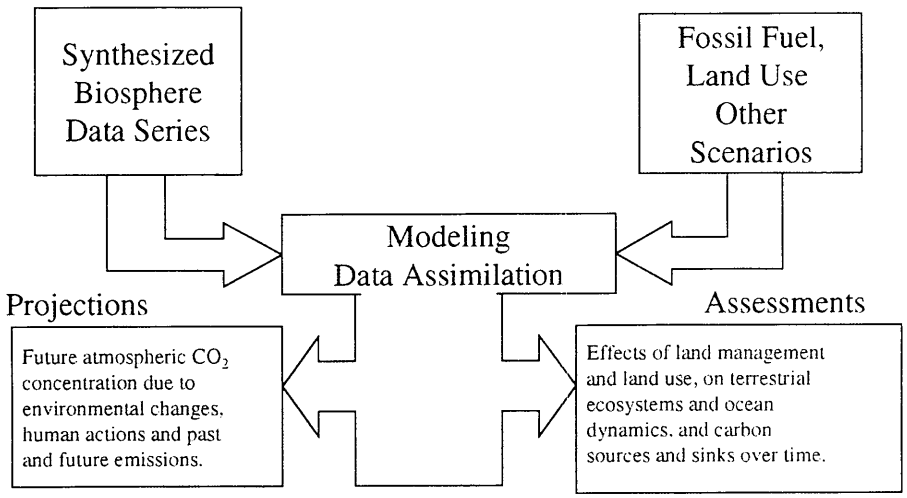
- Changes in climate with impacts on
  - Water Resources
  - Food and Fiber Production
  - Coastal Regions
  - Severe weather events
  - Land cover/Land use
  - Health
- Economic costs of mitigation, damages, and adaptation

"The costs and risks involved are difficult to quantify at this point..." *NAS 2001 report*

Rationalizing the Global Carbon Observing System

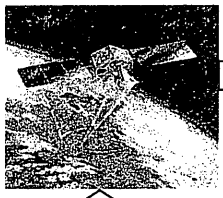
- **Field studies** and basic research elucidate processes responsible for carbon exchange
- Remotely sensed **imagery** and other spatial data products allow models to be **extrapolated** in space and time
- Trace gas concentration data from **flask sampling network** can be **inverted** as an integral **constraint** on models and extrapolation methods
- But we are currently **unable** to obtain a useful **overlap of scales** between process-based and integral methods

Projections and Assessments



Development and Validation

Developing, testing models and measurements

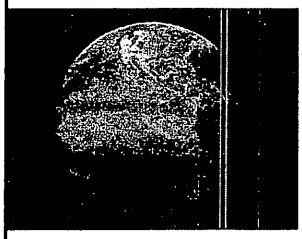


Satellite CO_2

Compare & Compute

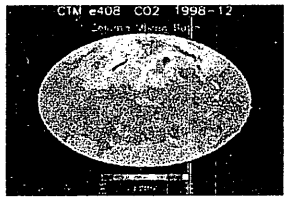
Accuracy

Predicted CO_2



Model Surface Carbon Flux, Winds

Data Assimilation



Satellite Biospheric Data

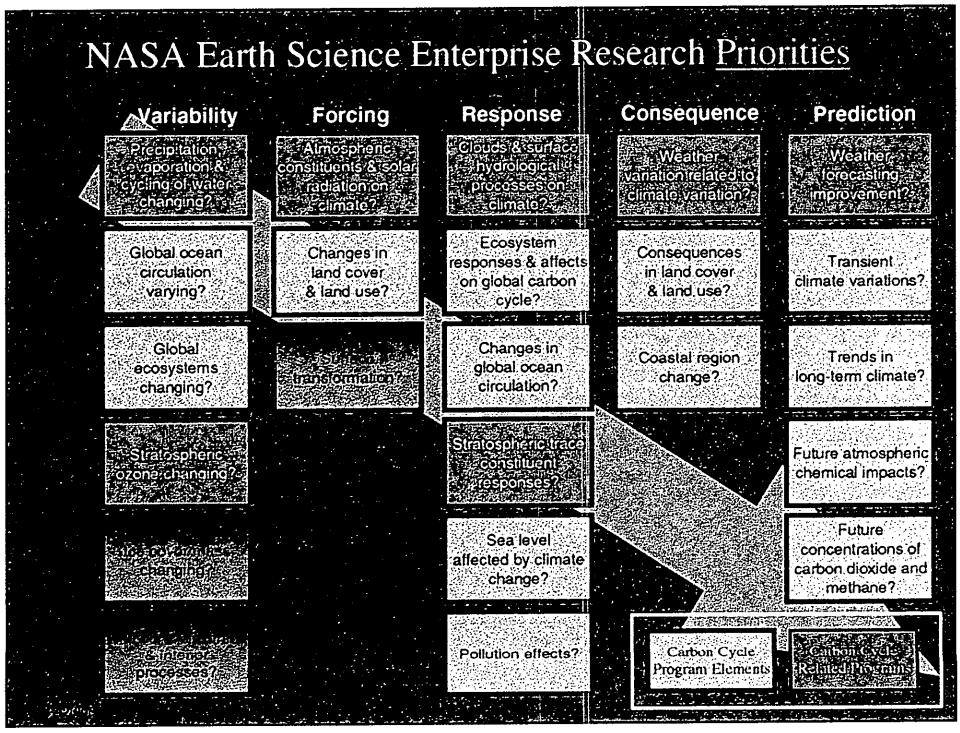
- *Vegetation Photosynthesis*
- *Ocean Photosynthesis*
- *Meteorology*
- *Temperature*
- *Cloudiness*

Field Campaigns

- *Validate Remote Sensing*
  - *With Ground observations*
  - *With Aircraft CO_2 Budgets*
- *Develop Remote Sensing Methods*
- *Develop Process Models*
- *Validate Models*
- *Calibrate Sensors*

NASA's Involvement is Critical.

- NASA programs and assets are critical to implement the carbon strategy
  - Earth Observing Systems
  - High-end Computing
  - Data Distribution Systems
  - Interdisciplinary Science Teams
- NASA has a recognized role in employing coupled land, ocean and atmosphere models for satellite observation analyses
- NASA has the capability required to develop the new observational technologies
  - Lasers
  - Microwave Sensors
  - Antennas
- NASA involvement complements ongoing NOAA, USDA, DOE, USGS and NSF efforts requiring NASA technology development and large, complex data sets



Ongoing Carbon Cycle Planning

- The U.S. Global Change Research Program has defined critical carbon cycle science questions and proposed a research strategy.
- An Interagency Working Group (IWG), including NASA, NOAA, DOE, USDA, NSF, USGS, has responded to the USGCRP.
  - Articulated Interagency Science Goals
  - Developed an Interagency Plan

USGCRP Science Questions

- What has happened to the CO_2 that has already been emitted by human activities?
- How do land management and land use, terrestrial ecosystems and ocean dynamics, and other factors affect carbon sources and sinks over time?
- What will be the future atmospheric CO_2 concentration resulting from environmental changes, human actions and past and future emissions?

USGCRP Science Goals

- 1. Quantify North American carbon sources and sinks and the processes controlling their dynamics.
- 2. Quantify the ocean carbon sink and the processes controlling its dynamics.
- 3. Quantify the global distribution of carbon sources and sinks and their temporal dynamics, and report the "state of the global carbon cycle" annually.
- 4. Evaluate the impact of land use change and land and marine resource management practices on carbon sources and sinks.
- 5.Project future atmospheric CO_2 concentrations and changes in terrestrial and marine carbon sinks.
- 6. Provide the scientific underpinning, and evaluations from specific test cases, for management of carbon in the environment.

Agency Activities and Assets

NASA

- Global time series (1972-2001) with (Landsat, SeaWiFS, EOS TERRA).
- Remote sensing research and airborne missions.
- Field campaigns - temperate, boreal, tropical ecosystems with interdisciplinary studies.
- Synthesis data sets.
- Ocean, terrestrial and atmospheric modeling/data assimilation.

NSF

- Fundamental earth science research, process studies, field campaigns, air-sea interactions, biodiversity research, National Center for Atmospheric Research.

USGS

- Landsat data repository, topography and land cover maps.

NOAA

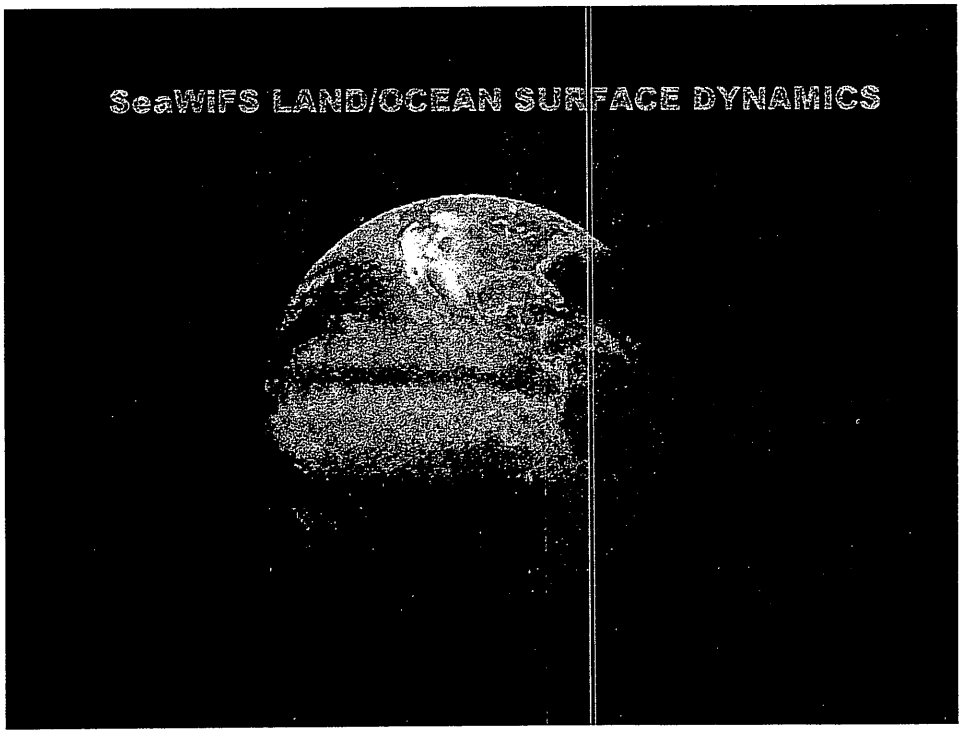
- Meteorological/climate data series.
- Sea surface temperature time series.
- Vegetation properties.
- Atmospheric CO_2 flask network.
- Ground and aircraft CO_2.
- Weather models (NCEP).
- Ocean CO_2 studies.

DOE

- Fossil fuel emissions, U.S. land cover, ground measurements of CO_2 exchange, carbon enhancement studies, carbon data bases.

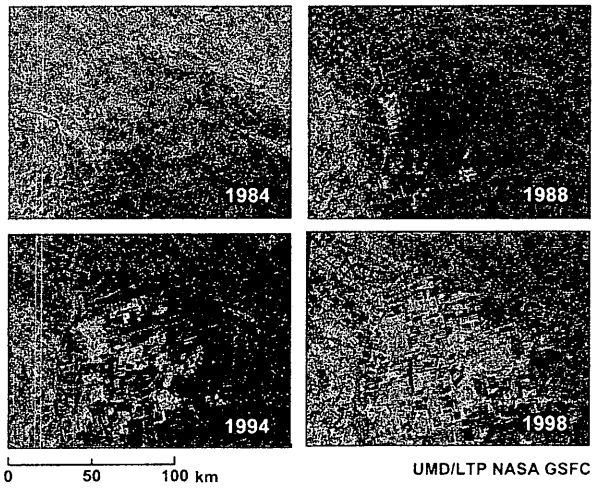
USDA

- Forest carbon inventories, remote sensing research, agricultural and carbon management studies, forest carbon cycle science and management research.



LAND COVER DISTURBANCE

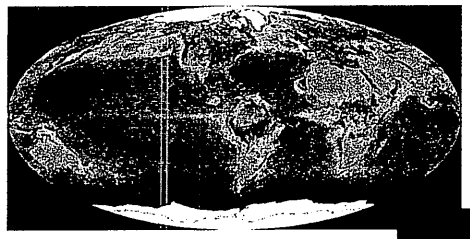
Landsat Land Cover Change
Santa Cruz, Bolivia 1984 -1998



UMD/LTP NASA GSFC

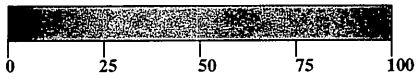
LAND/OCEAN CARBON MODELS

Boreal Summer



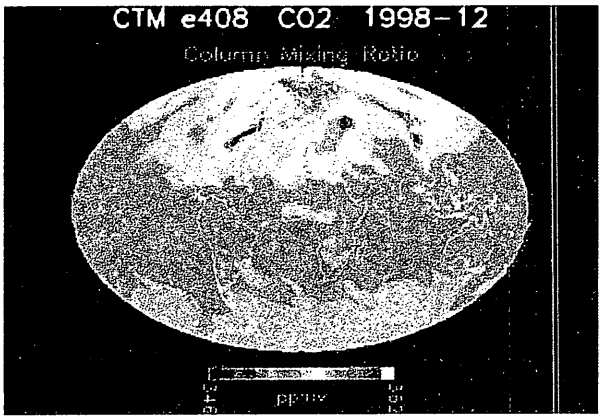
Biospheric net carbon fixation
for 1997-2000.
SeaWiFS land and ocean data.
Carnegie-Ames-Land and
Goddard-Rutgers-Ocean Models.

Austral Summer



NPP (gC m^{-2} $month^{-1}$)

Surface Flux and Atmospheric Transport Models



BASED ON:

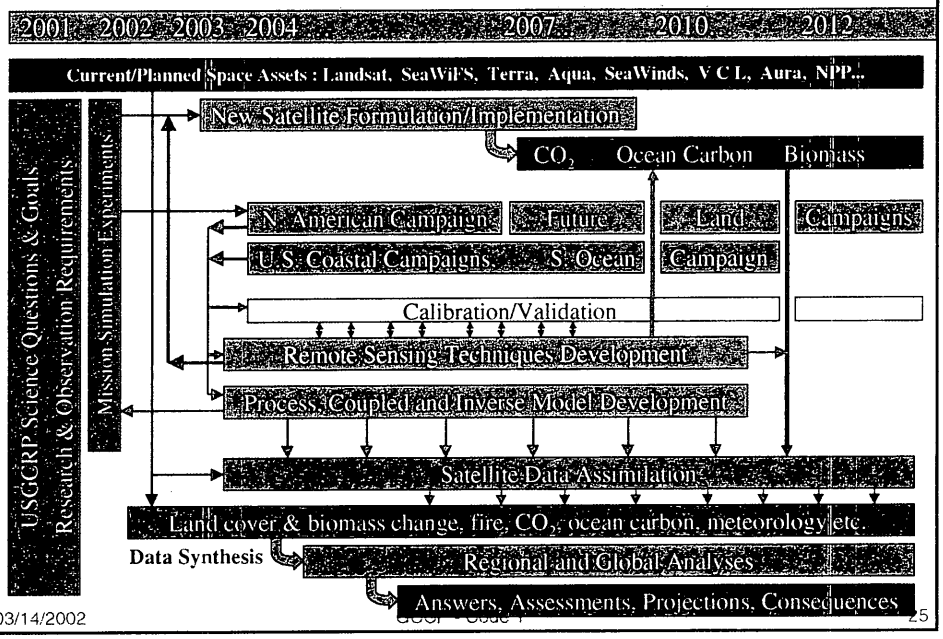
- Global wind fields
  - Weather data
  - Model assimilation
- Monthly Mean Fluxes
  - Ship measures of air-sea CO_2 difference and flux
  - Land Satellite data and ecosystem models
- Fossil Fuel Emissions

Critical Gaps

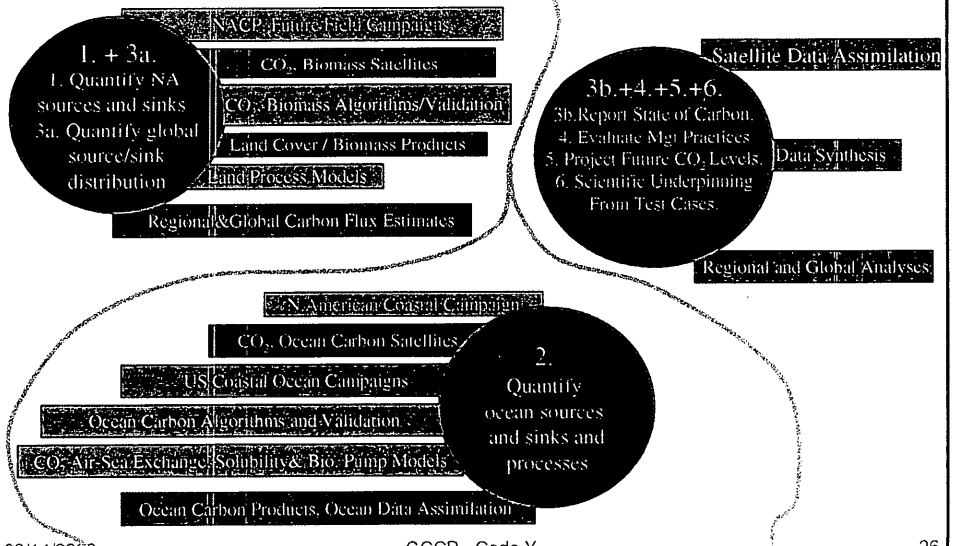
MISSING:	SOLUTION:
Global time series of CO_2 atmosphere-surface exchange.	Design and launch satellite to measure column and profile CO_2. Develop and use data assimilation techniques to generate surface flux fields.
MISSING:	SOLUTION:
Ecosystem carbon storage due to biomass and its change. Carbon consequences of disturbance.	Design and launch satellite to measure biomass and its change. Process on-orbit satellite data to map disturbance and recovery.
MISSING:	SOLUTION:
Measurements of critical biochemicals mediating global ocean surface layer uptake and export of carbon. Models of air-sea CO_2 exchange.	Develop satellite sensor to measure organic and inorganic compounds and models to compute carbon uptake. Develop exchange process models.

SUPPORTED BY FIELD CAMPAIGNS, CALIBRATION/VALIDATION EFFORTS, MODEL DEVELOPMENT AND DATA ASSIMILATION RESEARCH TO FULLY UTILIZE SATELLITE OBSERVATIONS

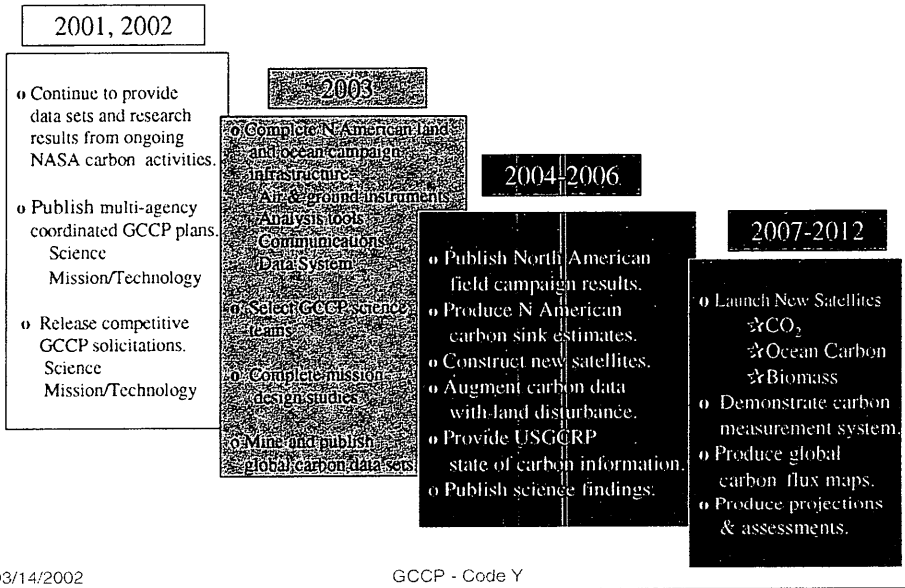
Science Activity Roadmap



GCCP Goals ⟷ Activities



GCCP Phased Deliverables

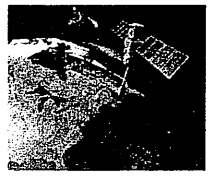


Missions/Technology

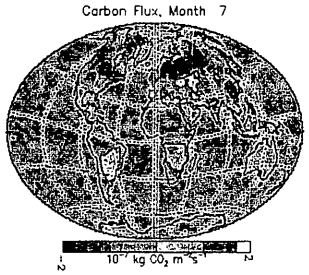
- Proof-of-concept or science demonstrations
  - Most observations require new technology
  - New missions phased as technology readiness matures
  - Comprehensive science missions require successful demonstrations
    - Reliable technology
    - Adequate measurement & algorithm precision and sampling
    - Successful data distribution and utilization to science community
    - Endorsement of science community
- Missions/technology to be selected through competitive process.
- Solicitations handled through usual NASA mechanisms.

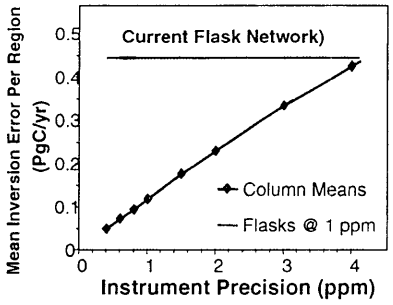
CO_2 FROM SPACE

Lidar Concept



Spectrometer Concept

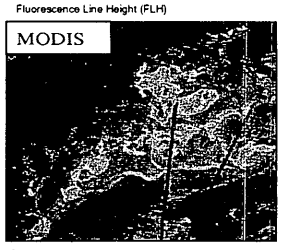


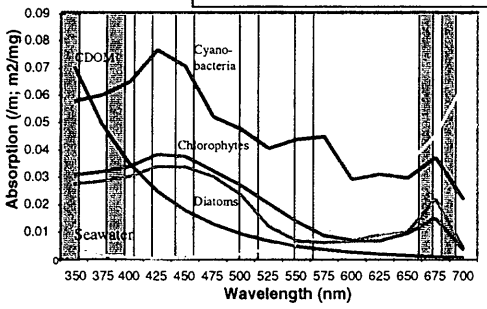


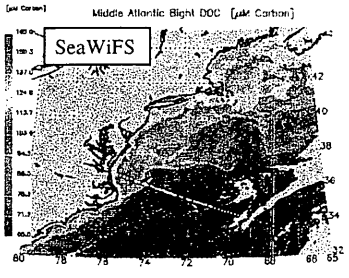
Ocean carbon from space

Bands/Capabilities Complimentary* to VIIRS
- Discrimination of terrestrial and open ocean dissolved organic matter (DOC)
- UV effects on marine photosynthesis
- Aeolian iron detection
- Estimation of photosynthetic efficiency from Fluorescence Line Height
- Lunar calibration (all bands)

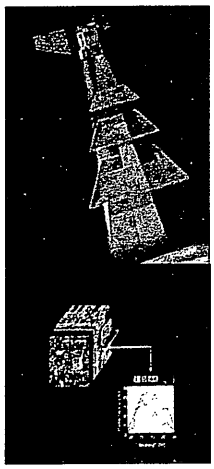
*not included in VIIRS



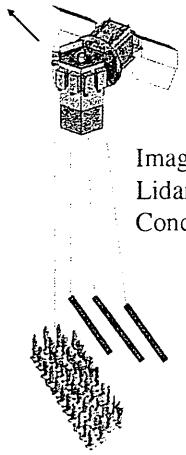




Biomass from Space

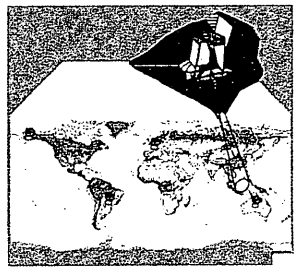


Hyperspectral Concept



Imaging Lidar Concept

P-band SAR with Profiling Lidar Concept



EXPECTED RESULTS

Characterize the most likely response of land and ocean CO_2 sources and sinks to climate change.

Provide quantitative understanding of processes that control variability of atmospheric CO_2 sources and sinks.

Reduce uncertainties in predictions of future levels of atmospheric CO_2 for specific emission scenarios.

Establish a sound scientific underpinning for management of carbon in the environment (e.g., reforestation, marine management, sequestration)

Provide the scientific basis to assess (quantify) the economic and societal impact of various carbon sequestration options

Policy implications:

NASA's charter is to provide objective scientific information to decision makers ... this information is needed to guide future international agreements designed to manage carbon in the environment.

Value to the Nation

A sound scientific basis to evaluate economic consequences of policy decisions.

- Agriculture
- Water resources
- Marine resources
- Energy
- Mitigation

A U.S. satellite-based assessment capability to provide independent assessment information for

- International treaty negotiations
- Compliance

U.S. must pursue a leadership role in carbon science to support its leadership role in global policy.

Backup

(Not included in this document. Some backup material is included in the companion document, "Cost Analysis for Recommended NASA Carbon Cycle Research")

APPENDIX 8. REFERENCES

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APPENDIX 9. ACRONYMS

ACRIMsat	Active Cavity Radiometer Radiance Monitor satellite
ACS	Attitude Control System
ADEOS	Advanced Earth Observing Satellite
AOL	Airborne Oceanographic Lidar
AIRS	Atmospheric Infrared Sounder
AIRSAR	Aircraft Synthetic Aperture Radar
AGCM	Atmospheric General Circulation Model
ALI	Advanced Land Imager
ALOS	Advanced Land Observation Satellite
ARC	Ames Research Center
AMSU	Advanced Microwave Sounding Unit
ARM/CART	Atmospheric Radiation Measurements/Cloud And Radiation Testbed
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATIP	Advanced Technology Initiatives Program
ATMS	Advanced Technology Microwave Sounder
ATS	Access To Space
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Advanced Visible and Infrared Imaging Spectrometer
BOREAS	Boreal Ecosystem-Atmosphere Study
BRDF	Bidirectional Reflectance Distribution Function
CDH	Command and Data Handling
CCM	Community Climate Model
CDIAC	Carbon Dioxide Information Analysis Center (DOE)
CDOM	Colored Dissolved Organic Matter
CEOS	Committee on Earth Observation Satellites
CLIVAR	Climate Variability and Predictability Program
CMDL	Climate Monitoring and Dynamics Laboratory (NOAA)
CNES	Centre National D'Etudes Spatiales
COBRA	CO_2 Budget and Rectification Airborne experiment
CrIS	Cross-track Infrared Sounder
CZCS	Coastal Zone Color Scanner
DAAC	Distributed Active Archive Center
DAO	Data Assimilation Office
DIAL	Differential Absorption Lidar
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
DOE	Department of Energy
ECMWF	European Centre for Medium Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
EO	Earth Orbiter
EOS	Earth Observing System
EOSDIS	EOS Data and Information System
ESSP	Earth System Science Pathfinder
ESTO	Earth Science Technology Office

ERBE	Earth Radiation Budget Experiment
ERS-1	European Remote aensing Satellite-1
ESE	Earth Science Enterprise
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organization (United Nations)
FASIR	Fourier-Adjustment, Solar zenith angle corrected, Interpolated Reconstructed
FIFE	First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment
FOCAL/ SEQUAL	Francais Ocean et Climat dans l'Atlantique Equatorial/ Seasonal Response of the Equatorial Atlantic Experiment
fPAR	Fraction of Photosynthetically Active Radiation
FPI	Fabry-Perot Interferometer
FTE	full-time equivalent
FTS	Fourier Transform Spectrometer
GAC	Global Area Coverage
GAIM	Global Analysis, Interpretation, and Modeling
GCCP	(NASA) Global Carbon Cycle Plan
GCM	General Circulation Model
GCOS	Global Climate Observing System
GISS	Goddard Institute for Space Studies
GEMS	Goddard Earth Modeling System
GEOS	Geodynamics Experimental Ocean Satellite
GEWEX	Global Energy and Water Cycle Experiment
GHCN	Global Historical Change Network
GLAS	Geoscience Laser Altimeter System
GLI	Global Imager
GMI	Global Modeling Initiative
GOES	Geostationary Operational Environmental Satellite
GPM	Global Precipation Mission
GPS	Global Positioning System
GRFM	Global Rain Forest Mapping (project)
GSFC	Goddard Space Flight Center
GTE	Global Tropospheric Experiment
GTOS	Global Terrestrial Observing System
HAPEX	Hydrological and Atmospheric Pilot Experiment
HIRDLS	High Resolution Dynamics Limb Sounder
HRPT	High Resolution Picture Transmission
HSB	Humidity Sounder Brazil
HTR	High Technology Readiness
IASI	Improved Atmospheric Sounding Interferometer
ICESat	Ice, Cloud and land Elevation Satellite
ICSU	International Council of Scientific Unions
IDS	Interdisciplinary Science
IFSARE	Interferometric SAR for Elevation
IGBP	International Geosphere-Biosphere Program
IGFA	International Group of Funding Agencies for Global Change Research

IGOS-P	Integrated Global Observing Strategy Partnership
IOC	Intergovernmental Oceanographic Commission (UNESCO)
IOCCG	International Ocean Color Coordinating Group
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre Simon Laplace
IRS	Indian Remote Sensing satellite
ISLSCP	International Satellite Land Surface Climatology Project
IWG	Ingeragency Working Group (USGCRP)
IHDP	International Human Dimensions Program
IIP	Instrument Incubator Program
IKONOS	ancient Greek word for image (not an acronym)
IMDC	Integrated Mission Design Center
IIP	Instrument Incubator Program
IPCC	Intergovernmental Panel on Climate Change
ISAL	Instrument Synthesis and Analysis Laboratory
ISLSCP	International Satellite Land Surface Climatology Project
JER-1	Japanese Earth Remote-sensing Satellite-1
JGOFS	Joint Global Ocean Flux Study
JPL	Jet Propulsion Laboratory
KSC	Kennedy Space Center
LAI	Leaf Area Index
LaRC	Langley Research Center
LBA	Largescale Biosphere atmosphere experiment in Amazonia
LCC	Life Cycle Cost
LCWG	Liquid Core Wave Guide
LEO	Low Earth Orbit
LIBS	Laser-Induced Breakdown Spectroscopy
LITE	Lidar In-space Technology Experiment
LVIS	Laser Vegetation Imaging Sensor
LSPs	Land Surface Parameterizations
LTER	Long Term Ecological Research program
MAPS	Measurement of Air Pollution from Satellites
MBLA	Multi-Beam Laser Altimeter
MERIS	Medium-Resolution Imaging Spectrometer
MICM	Multi-Instrument Cost Model
MISR	Multi-angle Imaging Spectroradiometer
MLS	Microwave Limb Sounder
MOBY	Marine Optical Buoy
MODIS	Moderate-Resolution Imaging Spectroradiometer
MOPITT	Measurements of Pollution in the Troposphere
MOS	Modular Optoelectronic Scanner
MRLC-NLCD	Multi-Resolution Land Characterization-National Land Cover Data
MSFC	Marshall Space Flight Center
NACP	North American Carbon Program
NASA	National Aeronautics and Space Administration

NASDA	National Space Development Agency (Japan)
NCAR	National Center for Atmospheric Research
NCCS	NASA Center for Computational Services
NDSC	Network for Detection of Stratospheric Change
NDVI	Normalized Difference Vegetation Index
NEE	Net Ecosystem Exchange
NIMA	National Imagery and Mapping Agency
NMHC	Non-Methane HydroCarbons
NMP	New Millennium Program
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NPP	Net Primary Productivity
NPG	NASA Program Guideline
NRC	National Research Council
NSF	National Science Foundation
NSIPP	NASA Seasonal to Interannual Prediction Program
NWP	Numerical Weather Prediction
OBOM	Ocean Biogeochemical/Optical Model
OCM	Ocean Colour Monitor
OCTS	Ocean Color and Temperature Scanner
OGCM	Ocean General Circulation Models
OLR	Outgoing Longwave Radiation
OMI	Ozone Monitoring Instrument
OSC	Orbital Sciences Corporation
OSSE	Observing System Simulation Experiment
PAR	Photosynthetically Available Radiation
PARABOLA	Portable Apparatus for Rapid Acquisition of Bidirectional Observations of the Land and Atmosphere
PARASOL	Polarization and Anisotropy of Reflectances for atmospheric Science coupled with Observations
PBL	Planetary Boundary Layer
POC	Particulate Organic Carbon
RAO	Resource Analysis Office
RSDO	Rapid Spacecraft Development Office
SAGE	Stratospheric Aerosol and Gas Experiment
SAP	Superactive-passive Airborne sensor
SAR	Synthetic Aperture Radar
SBIR	Small Business Innovation Research
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SiB	Simple Biosphere (model)
SIMBIOS	Sensor Intercocmparison and Merger for Biological and Interdisciplinary Oceanic Studies
SeaDAS	SeaWiFS Data Analysis System
SEASAT	Sea Satellite
SeaWiFS	Sea-viewing Wide Field-of-view Sensor

SIR	Shuttle Imaging Radar
SLA	Shuttle Laser Altimeter
SPARCLE	Space Readiness Coherent Lidar Experiment
SMMR	Scanning Multi-channel Microwave Radiometer
SRTM	Shuttle Radar Topography Mission
SSC	Stennis Space Center
SSH	Sea Surface Height
SSM/I	Special Sensor Microwave/Imager
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SSW	Sea Surface Winds
SWIR	Short Wave Infrared
TES	Tropospheric Emission Spectrometer
TIR	Thermal Infrared Radiation
TIROS	Television Infrared Observation Satellite
TOMS	Total Ozone Mapping Spectrometer
TOPEX	Ocean Topography Experiment
TRL	Technology Readiness Level
TRMM	Tropical Rain Measurement Mission
TRWIS	TRW Imaging Spectrometer
UNEP	United National Environment Program
USDA	US Department of Agriculture
USGCRP	US Global Change Research Program
USGS	US Geologic Survey
VCL	Vegetation Canopy Lidar
VIIRS	Visible and Infrared Imaging Radiometer Suite
VHRR	Very High Resolution Radiometer
VNIR	Visible & Near Infrared
WCRP	World Climate Research Program
WFF	Wallops Flight Facility
WMO	World Meteorological Organization

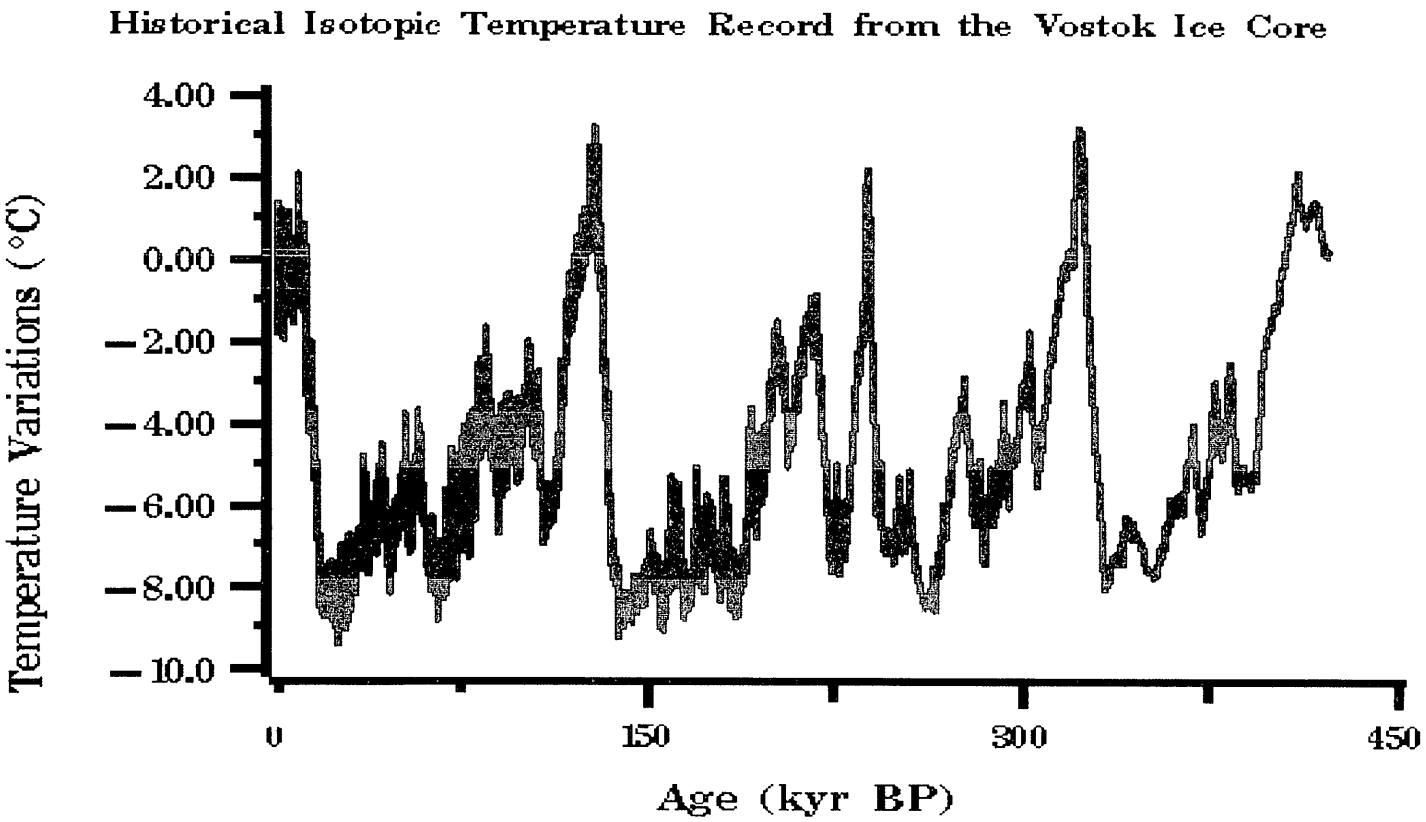


Figure 1. Variation with time of the Vostok isotope temperature record for the past 420,000 years (Petit et al, 1999) as a difference from the modern surface temperature value of -55.5°C. Note that the x-axis increases backwards in time from the present.

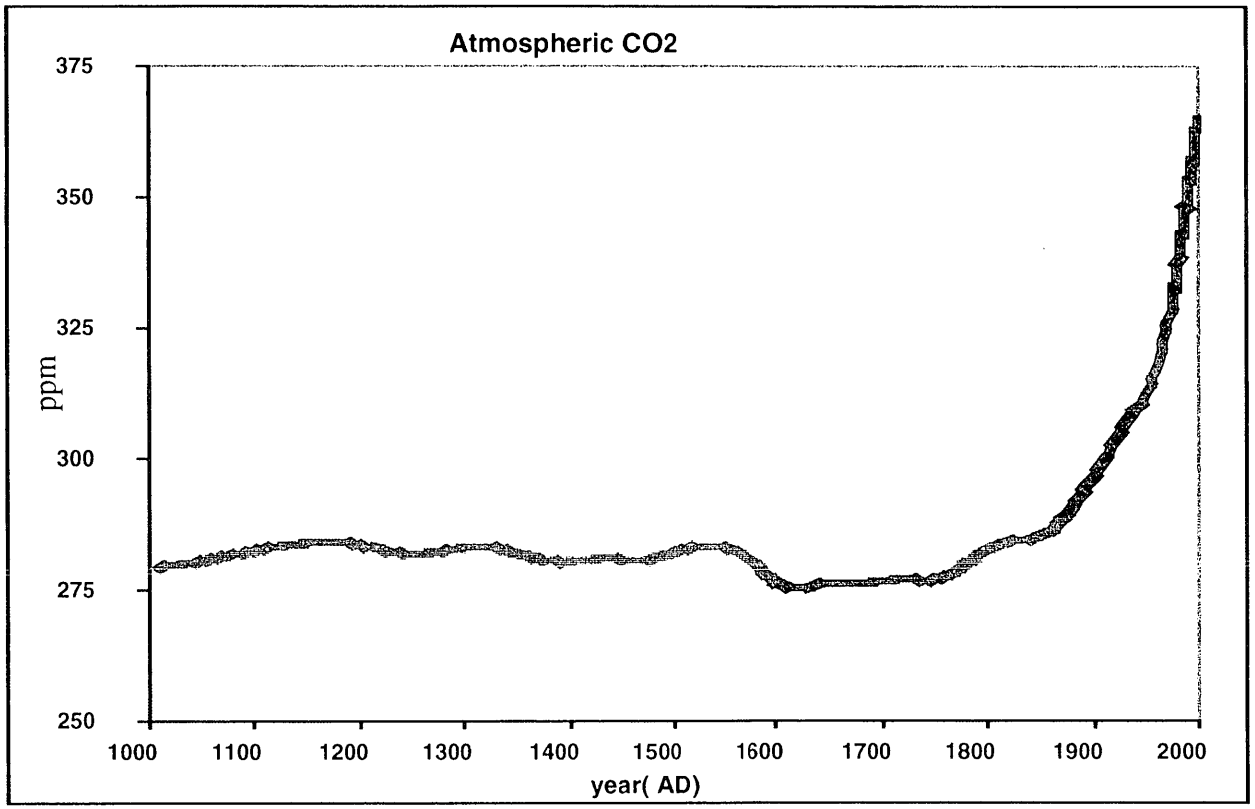


Figure 2. Atmospheric CO_2 concentrations in the last millennium

Figure 3. What Drives Change in the Climate System?

Earth's Heat Balance = **Warming** - **Cooling**

Warming:

Greenhouse gases

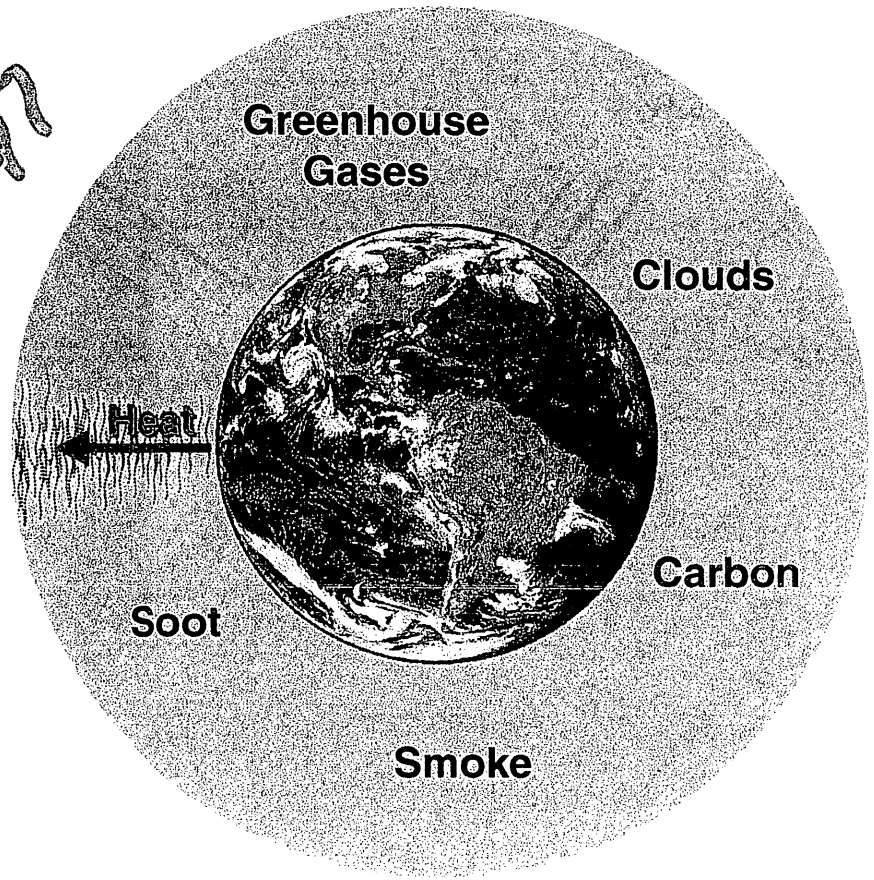
Absorbing aerosols

Greenhouse Gases

- Carbon dioxide CO_2
- Methane CH_4
- Water Vapor H_2O
- Nitrous Oxide N_2O
- Chloroflorocarbons CFC's
- Ozone O_3

Absorbing Aerosols

- Smoke
- Soot



Cooling:

Reflective aerosols

Natural carbon sequestration

Reflective Aerosols

- Impact on cloud formation
- Dust
- Volcanic aerosols SO_2

Natural carbon sequestration

- Forests/Soils
- Air-sea CO2 equilibrium
- Ocean Biota

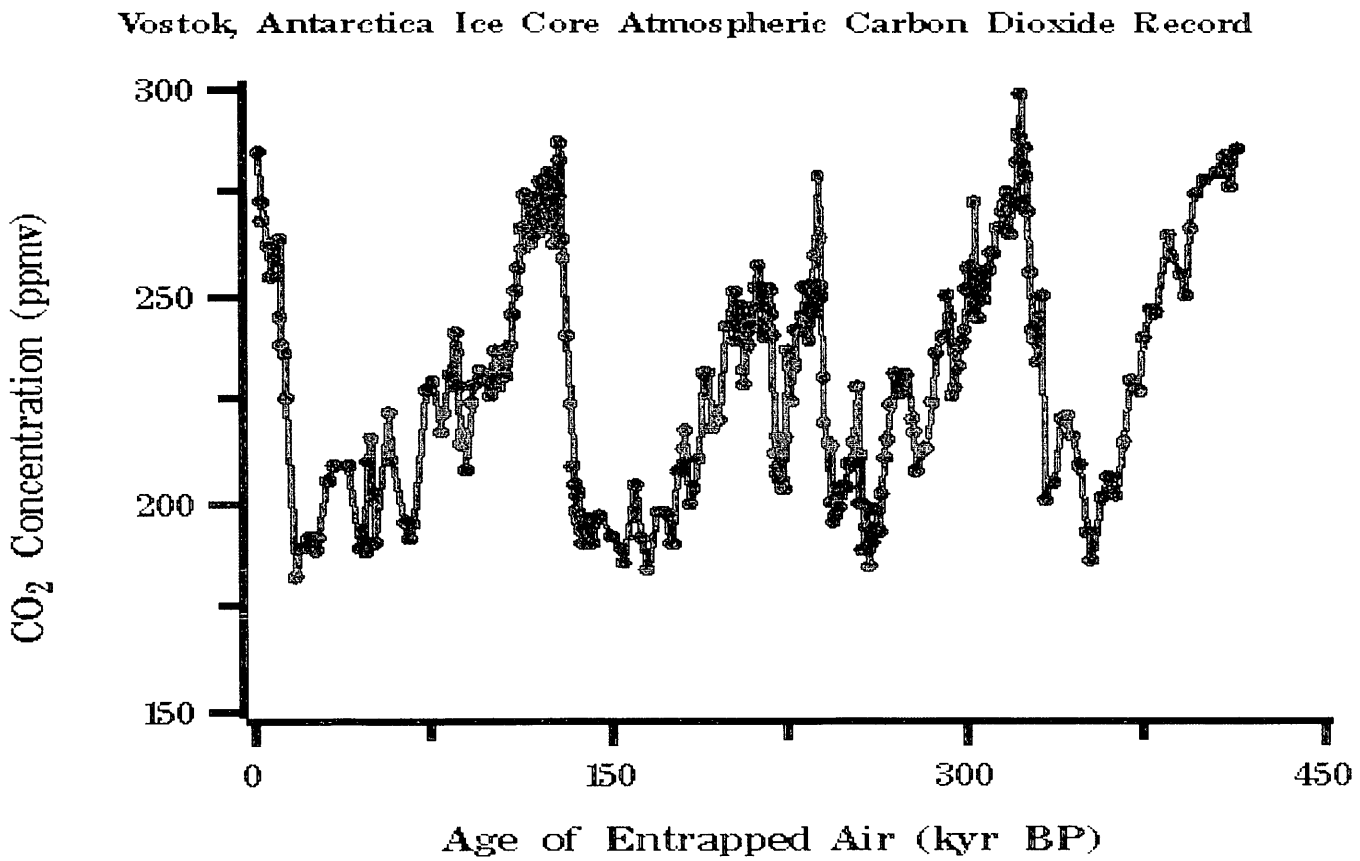


Figure 4. Vostok ice core record of the Earth's atmospheric CO_2 concentrations for the past 420,000 years (Petit et al., 1999). Note that the x-axis increases backwards in time from the present.

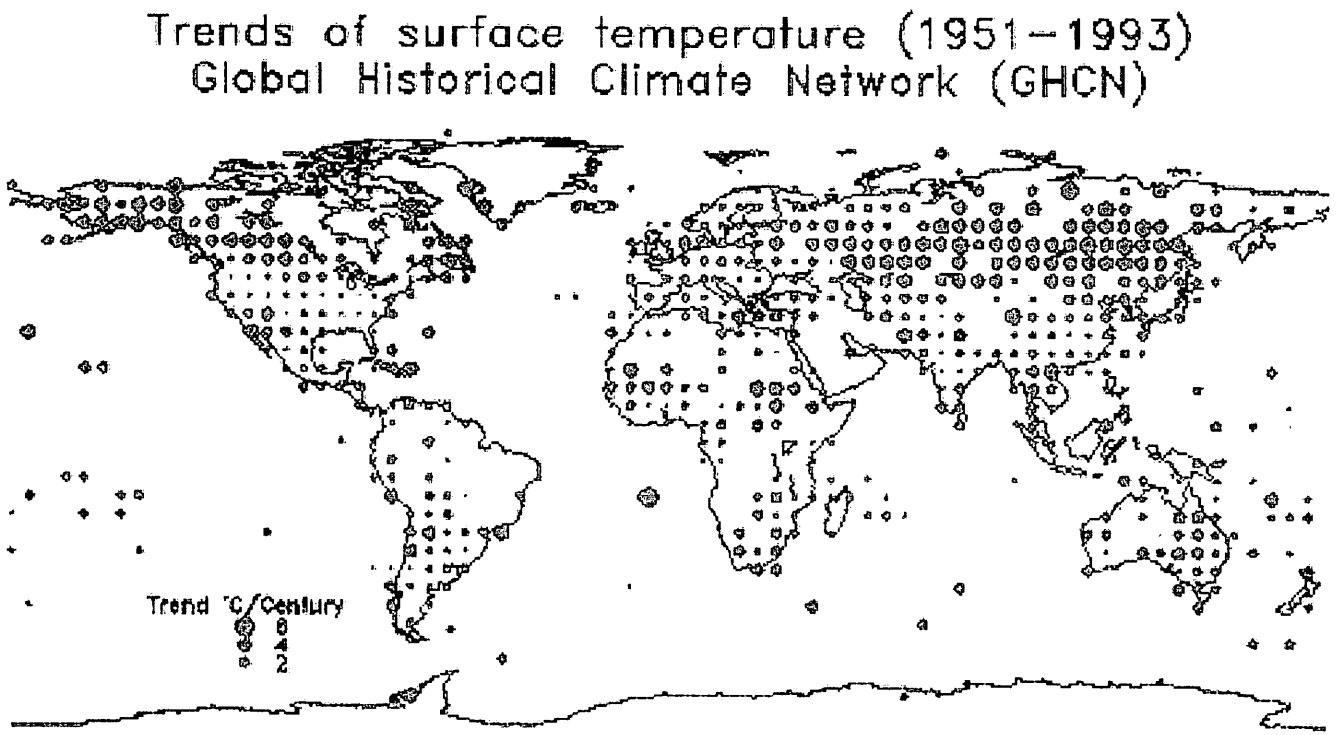


Figure 5. Observed regional trends in surface temperature in the past 40 years

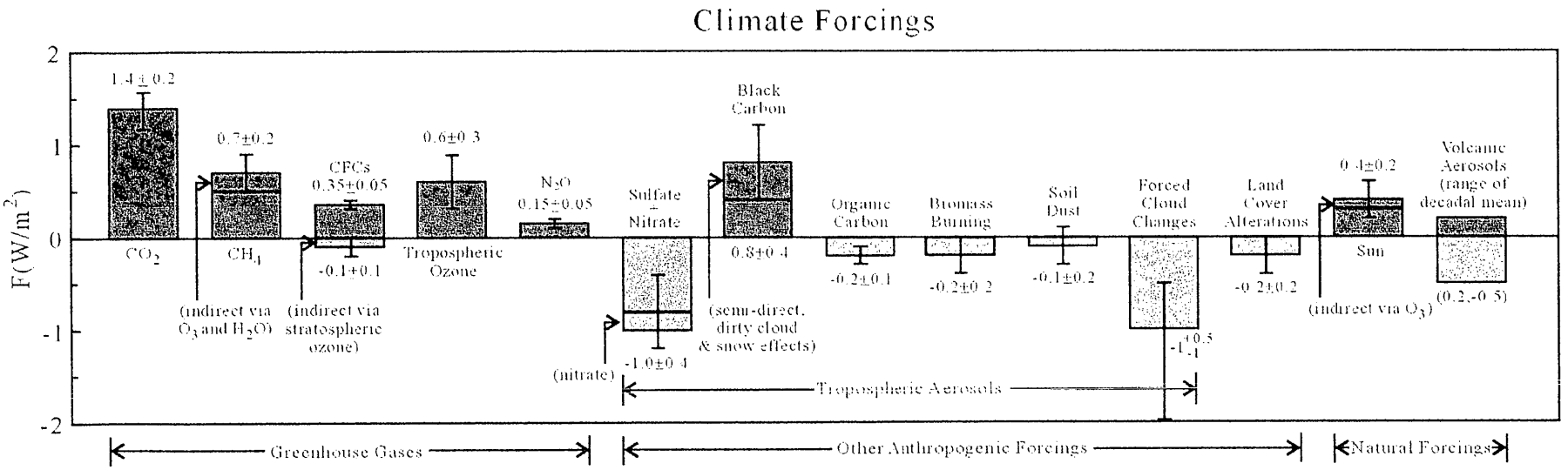


Figure 6. Climate forcing magnitudes of warming (red) and cooling (blue) factors from 1850 to present with uncertainty bars

Figure 7. The Global Carbon Cycle

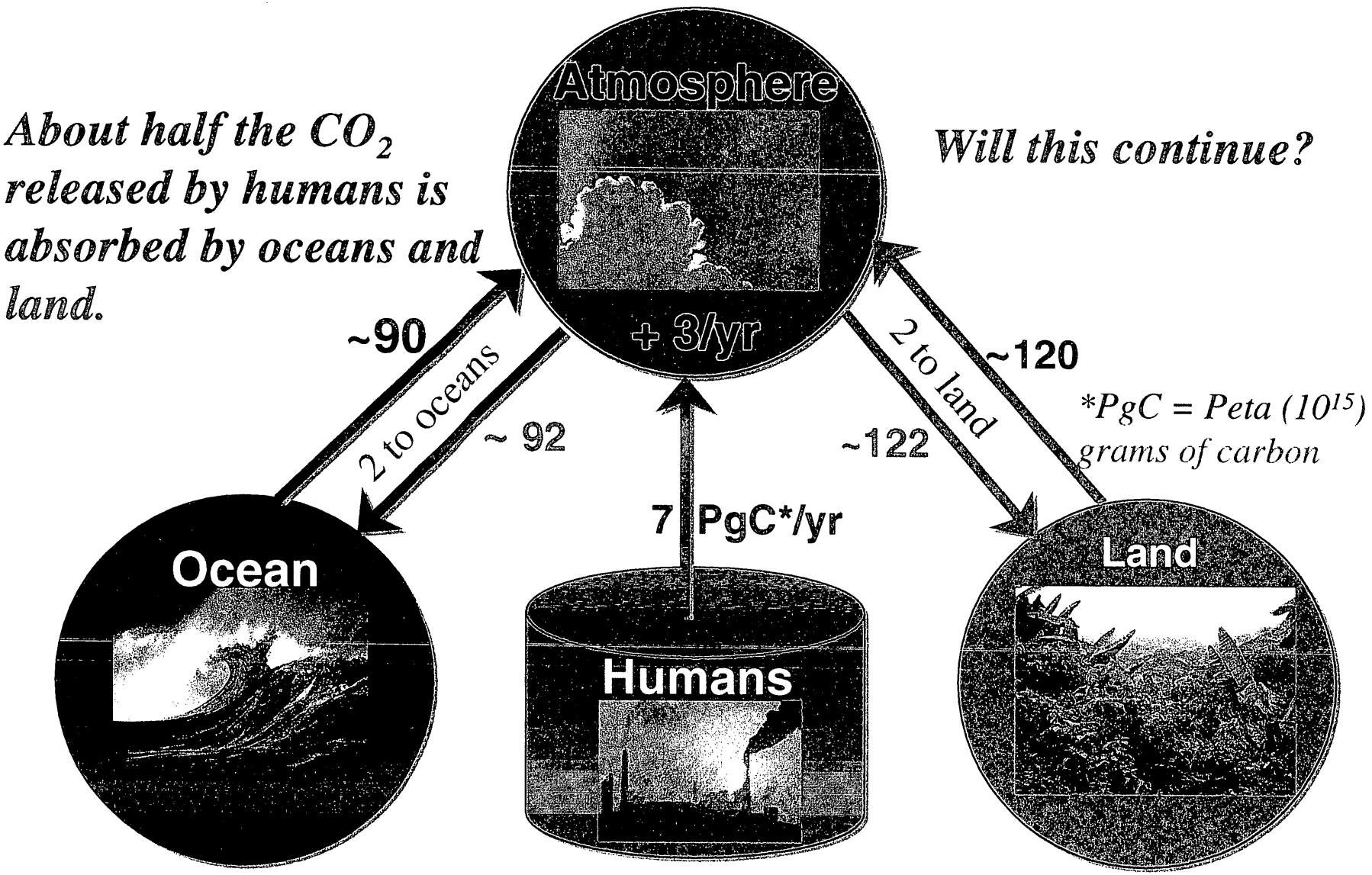
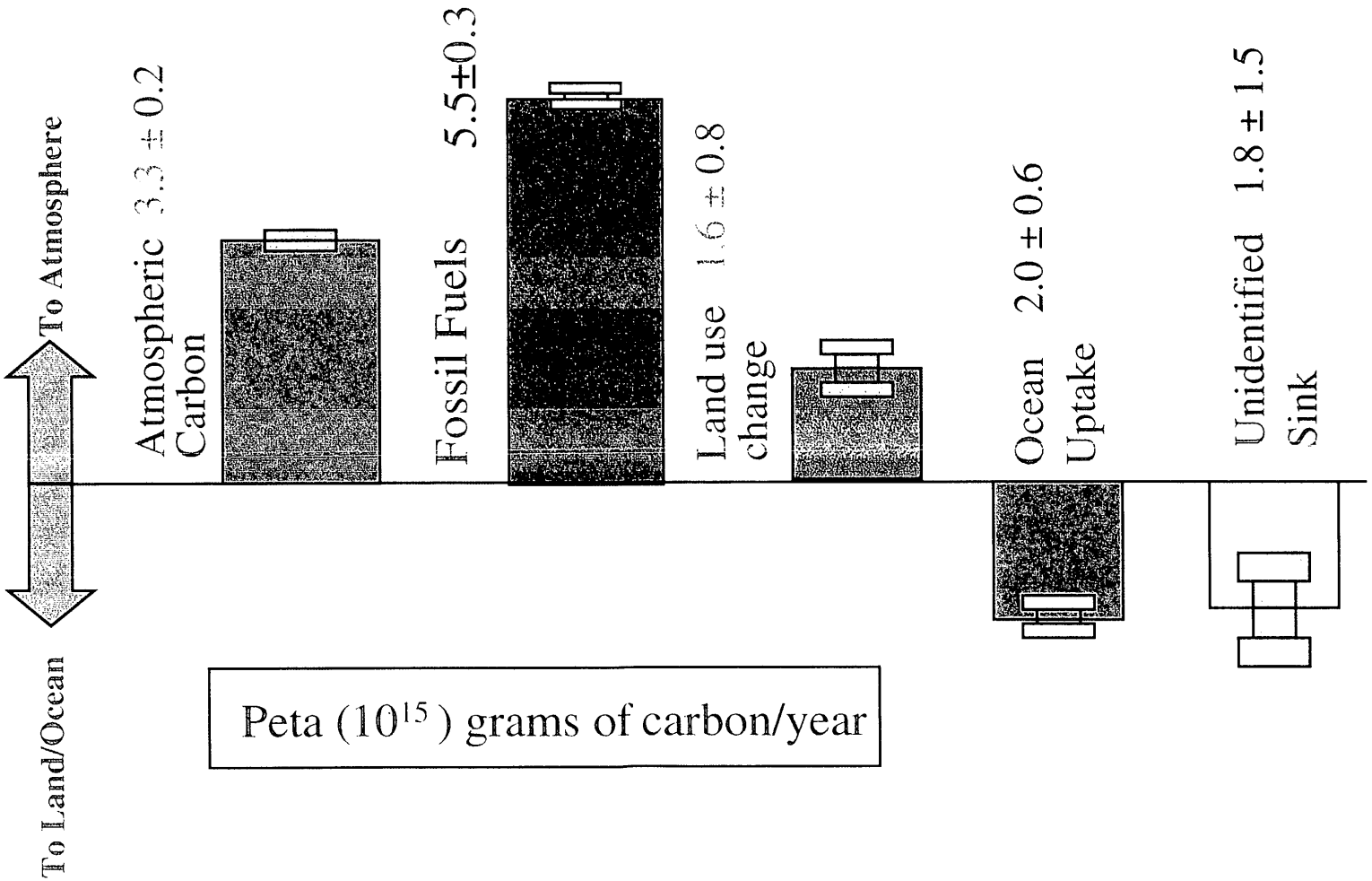


Figure 8. Current Carbon Fluxes and Uncertainties

- Current source and sink strengths are uncertain.
- Prediction of future climate forcing is therefore uncertain as well.



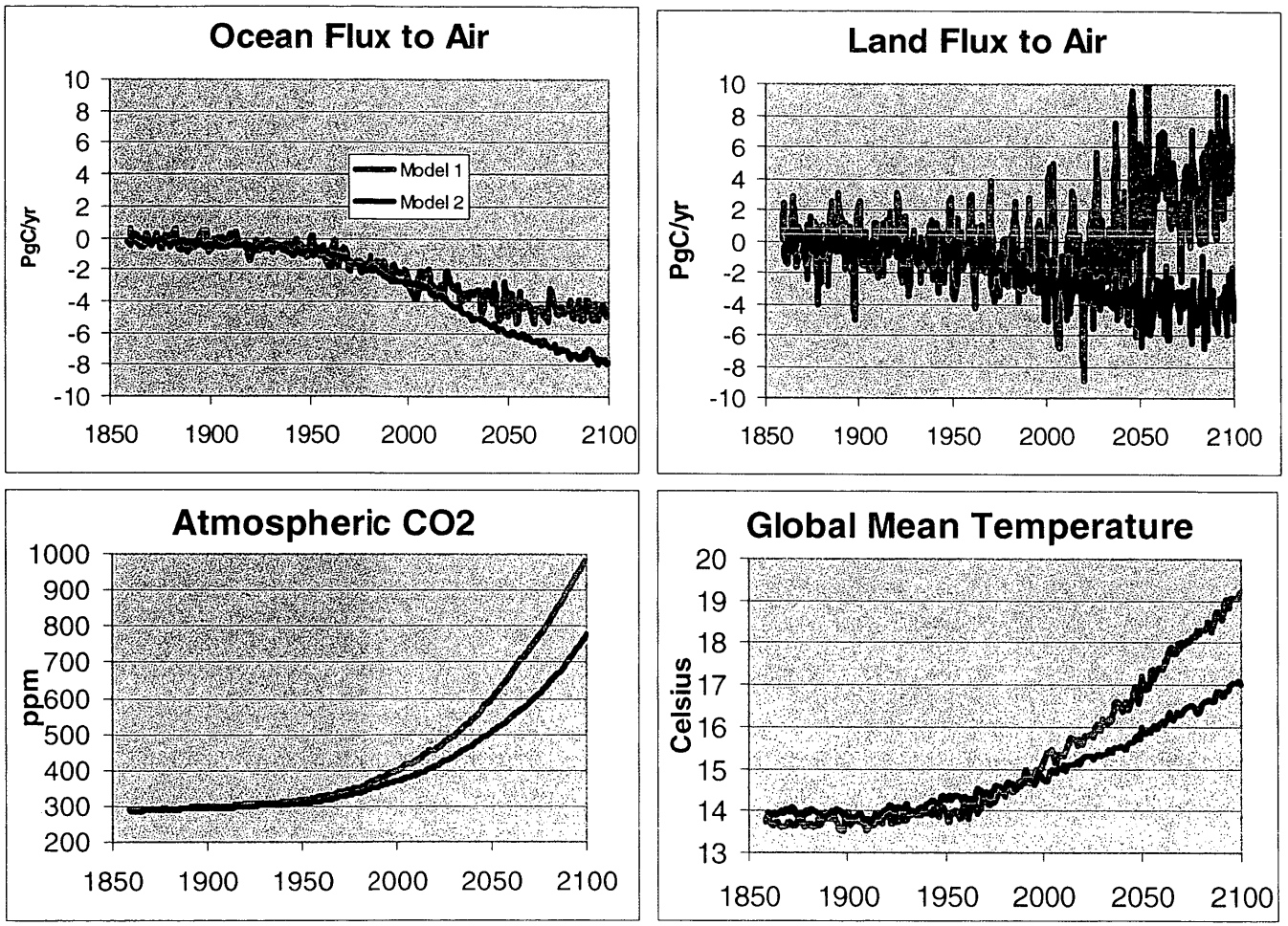


Figure 9. Hadley Center and IPSL climate model predictions

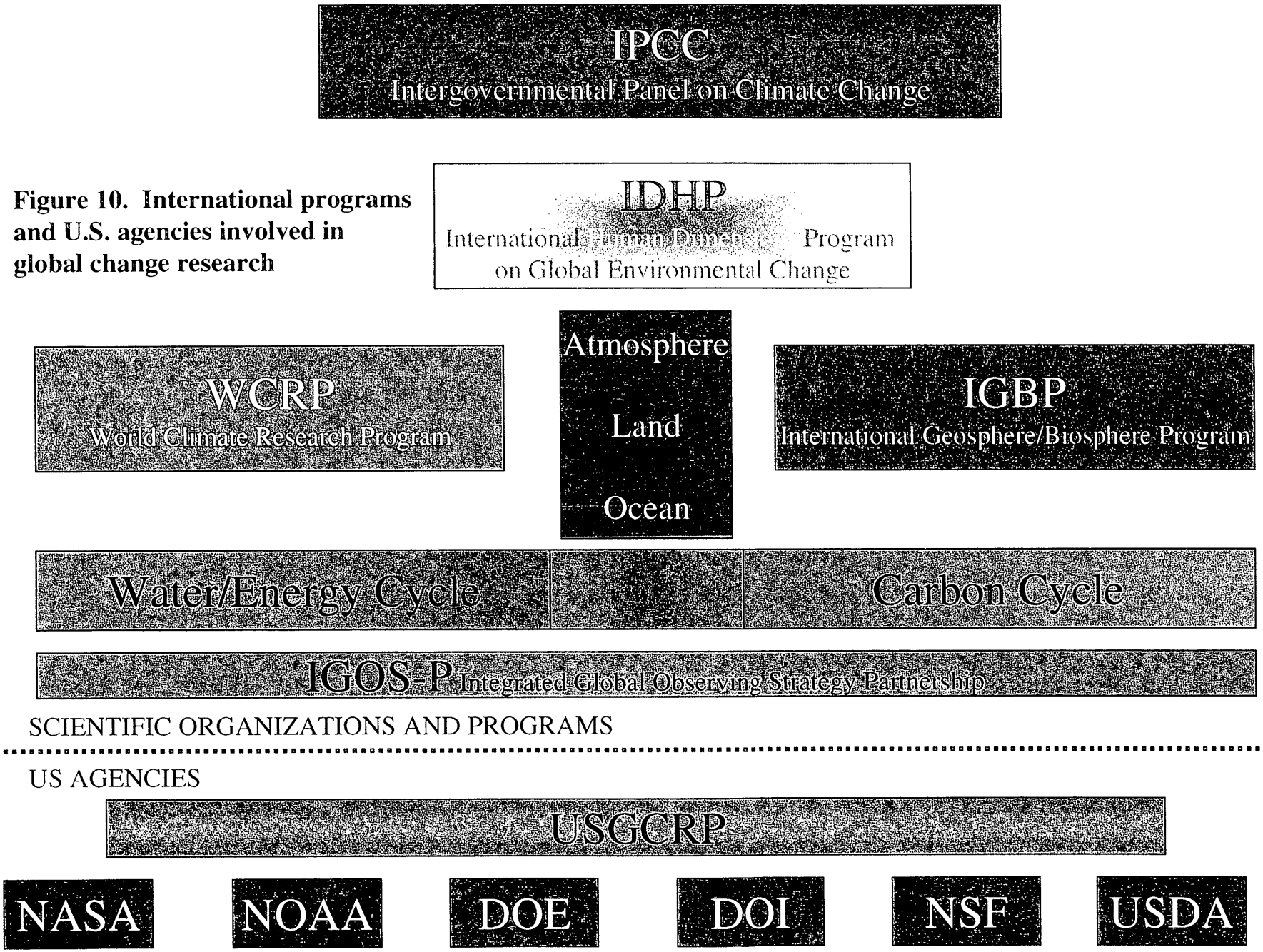
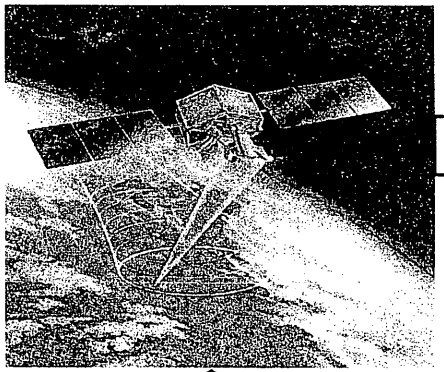


Figure 10. International programs and U.S. agencies involved in global change research

Figure 11. GCCP Carbon Analysis Framework

Developing/testing models and measurements

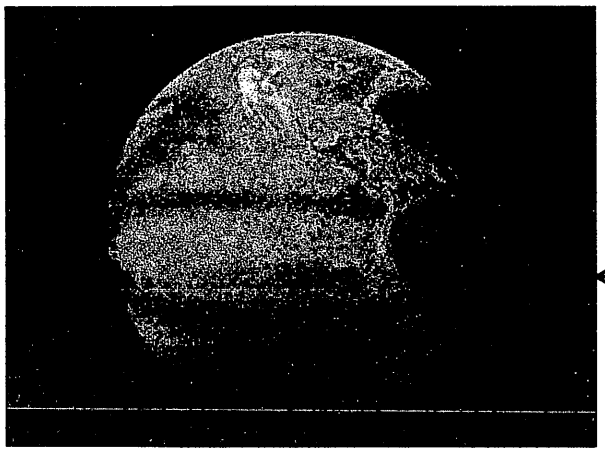


Satellite CO_2

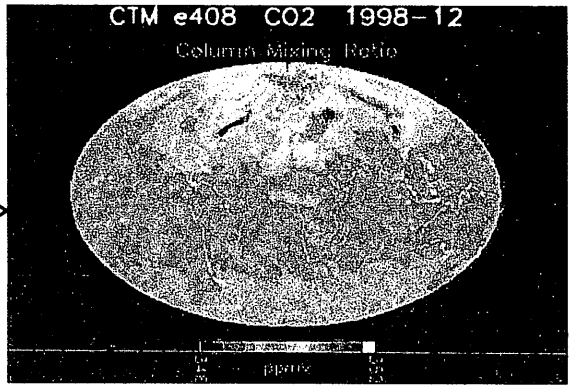
Compare & Compute

Accuracy

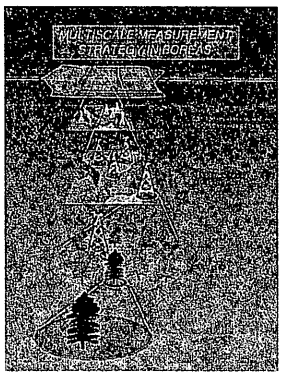
Predicted CO_2



Model Surface Carbon Flux, Winds
Data Assimilation



Satellite Biospheric Data
- *Vegetation Photosynthesis*
- *Ocean Photosynthesis*
- *Meteorology*
- *Temperature*
- *Cloud Cover*



Field Campaigns
- *Validate Remote Sensing*
  - *With Ground observations*
  - *With Aircraft CO_2 Budgets*
- *Develop Remote Sensing Methods*
- *Develop Process Models*
- *Validate Models*
- *Calibrate Sensors*

Figure 12. Critical Gaps

- MISSING:
  - Global time series of CO_2 atmosphere-surface exchange.
- MISSING:
  - Ecosystem carbon storage due to biomass and its change.
  - Carbon consequences of disturbance.
- MISSING:
  - Measurements of critical biochemicals mediating global ocean surface layer uptake and export of carbon.
  - Models of air-sea CO_2 exchange.
- SOLUTION:
  - Design and launch satellite to measure column and profile CO_2.
  - Develop and use data assimilation techniques to generate surface flux fields.
- SOLUTION:
  - Design and launch satellite to measure biomass and its change.
  - Process on-orbit satellite data to map disturbance and recovery.
- SOLUTION:
  - Develop satellite sensor to measure organic and inorganic compounds and models to compute carbon uptake.
  - Develop exchange process models.

SUPPORTED BY FIELD CAMPAIGNS, CALIBRATION/VALIDATION EFFORTS, MODEL DEVELOPMENT AND DATA ASSIMILATION RESEARCH TO FULLY UTILIZE SATELLITE OBSERVATIONS.

Figure 13. Proposal Definition Organization

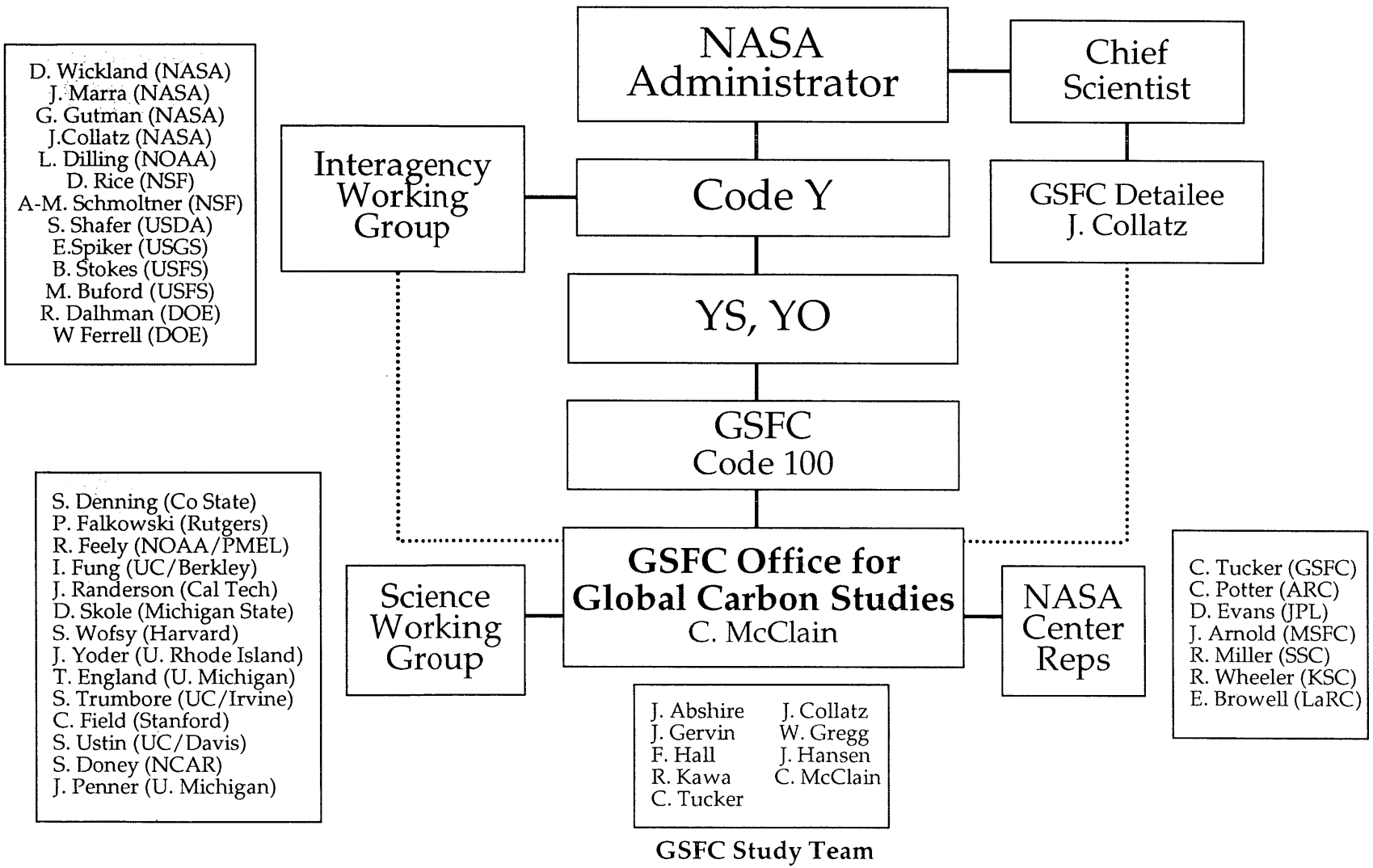


Figure 14. Proposal Development Process

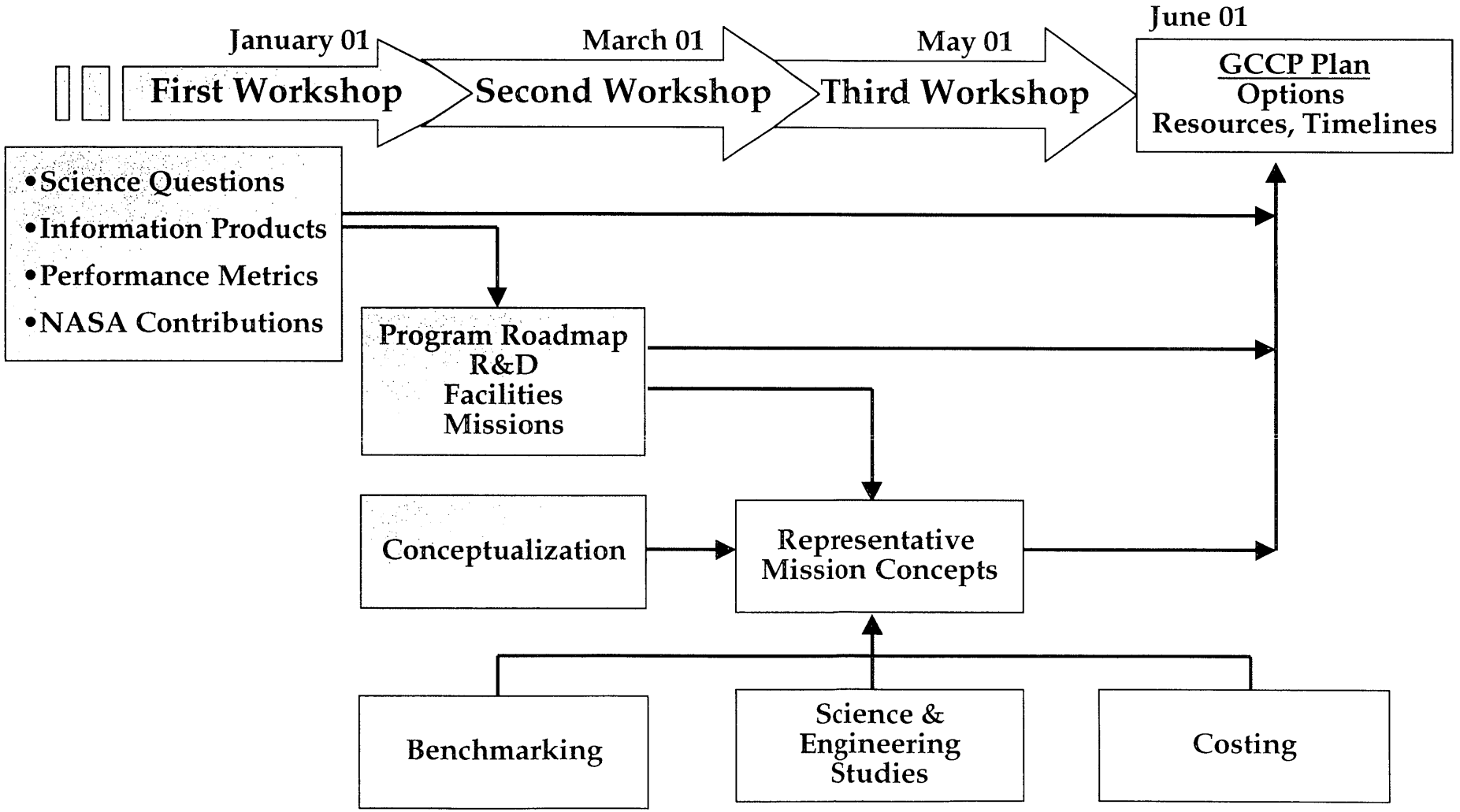


Figure 15. Science Activity Roadmap

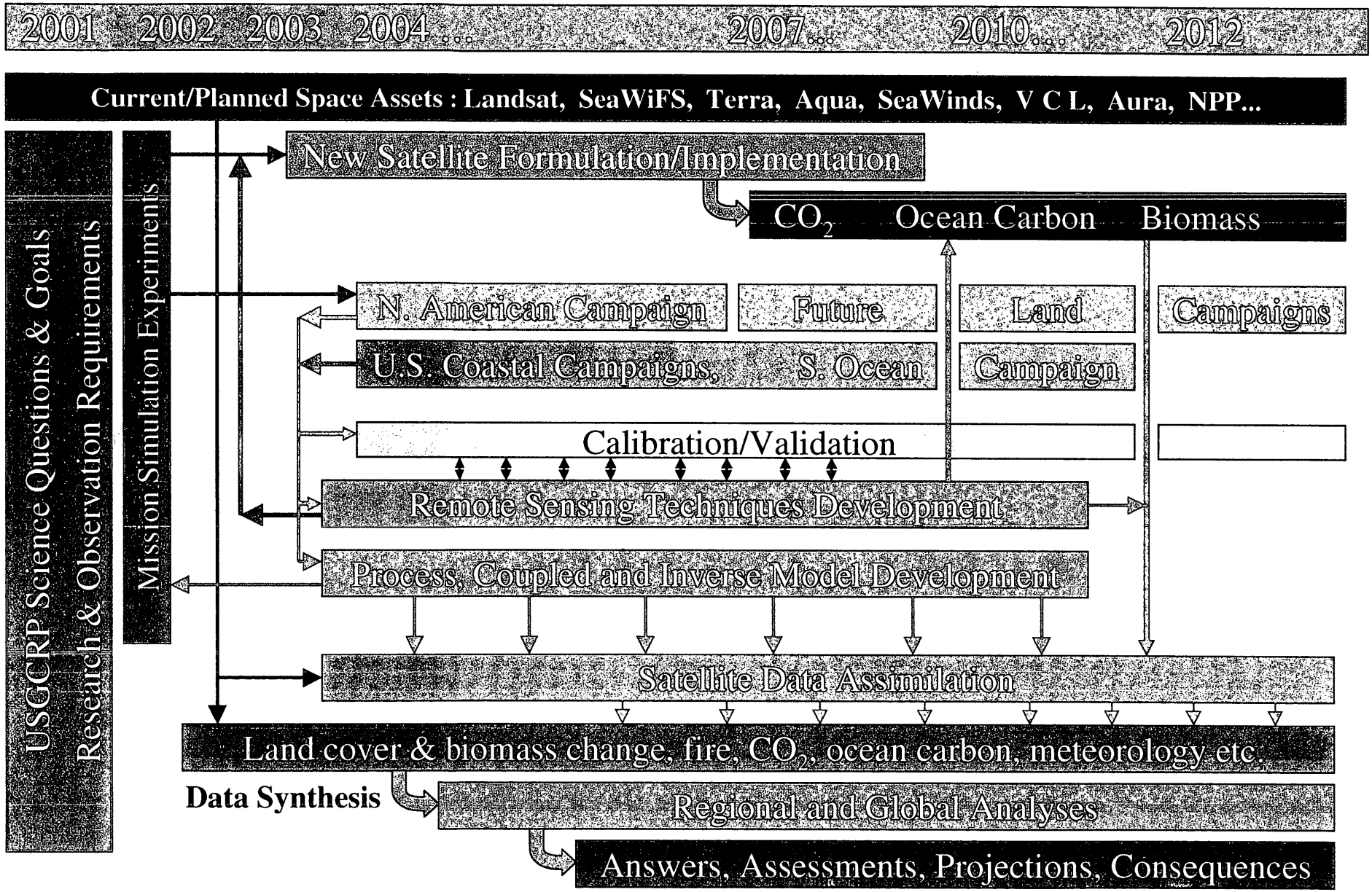


Figure 16. Technology Roadmap

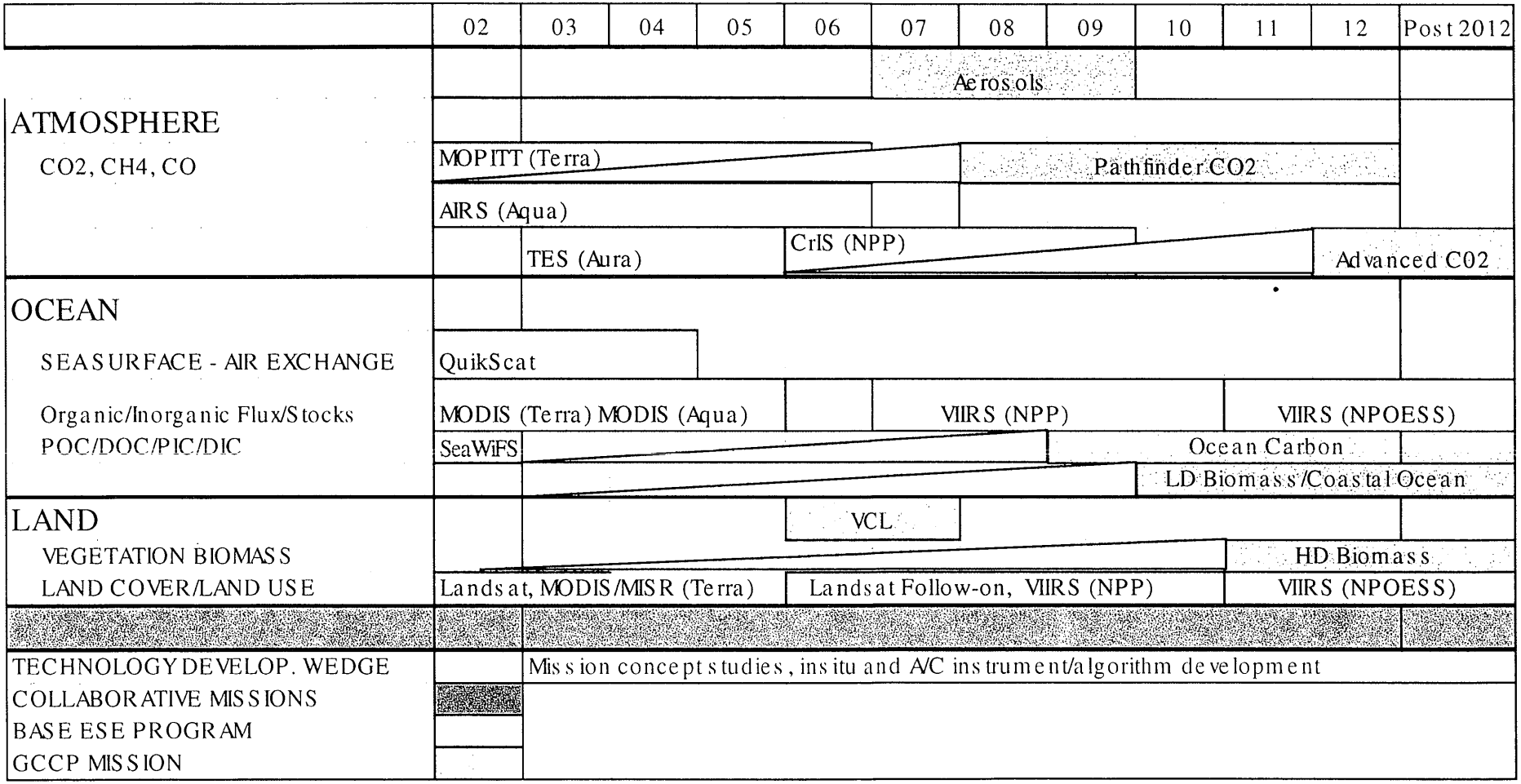
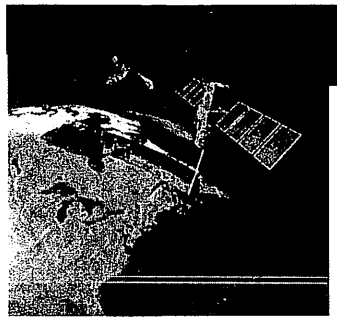


Figure 17. Notional Missions



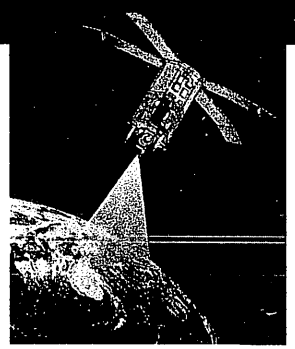
Pathfinder CO_2

Mission Life: 5 Years

Orbit: 705 km polar, sun-synchronous, with a 12:00 noon crossing time

Space Access: Pegasus XL or equivalent

Mission Options: Single dedicated mission or as a complementary instrument on the Ocean Carbon mission.



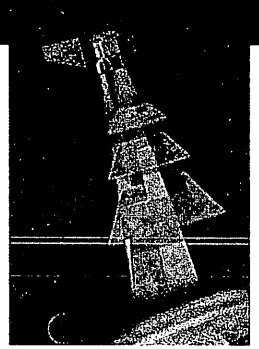
Ocean Carbon

Mission Life: 5 Years

Orbit: 705 km polar, sun-synchronous, with a 12:00 noon crossing time

Space Access: Pegasus XL or equivalent

Mission Options: A single instrument mission or a combined mission that includes the Pathfinder CO_2 measurement



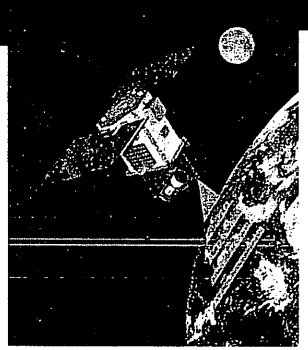
Low Density Biomass
Coastal Ocean

Mission Life: 5 Years

Orbit: 705 km circular sun-synchronous with a 10:30 a.m. descending node

Space Access: Taurus or equivalent

Key Technologies: Large area focal plane arrays, large capacity on-board recorders, and high rate downlink systems.



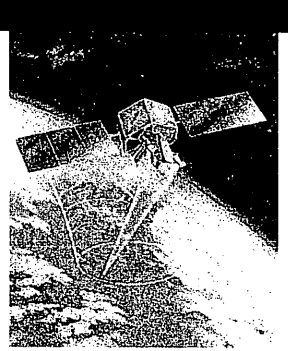
High Density Biomass

Mission Life: 3 Years

Orbit: 400 km polar sun-synchronous with a 6:00 p.m. ascending node

Space Access: Delta II or equivalent.

Key Technologies: P-band polarimetric SAR, pixelated detectors, high-accuracy attitude & position package, laser diode ε & life-time improvement, & an S-band low power transceiver



Advanced CO_2

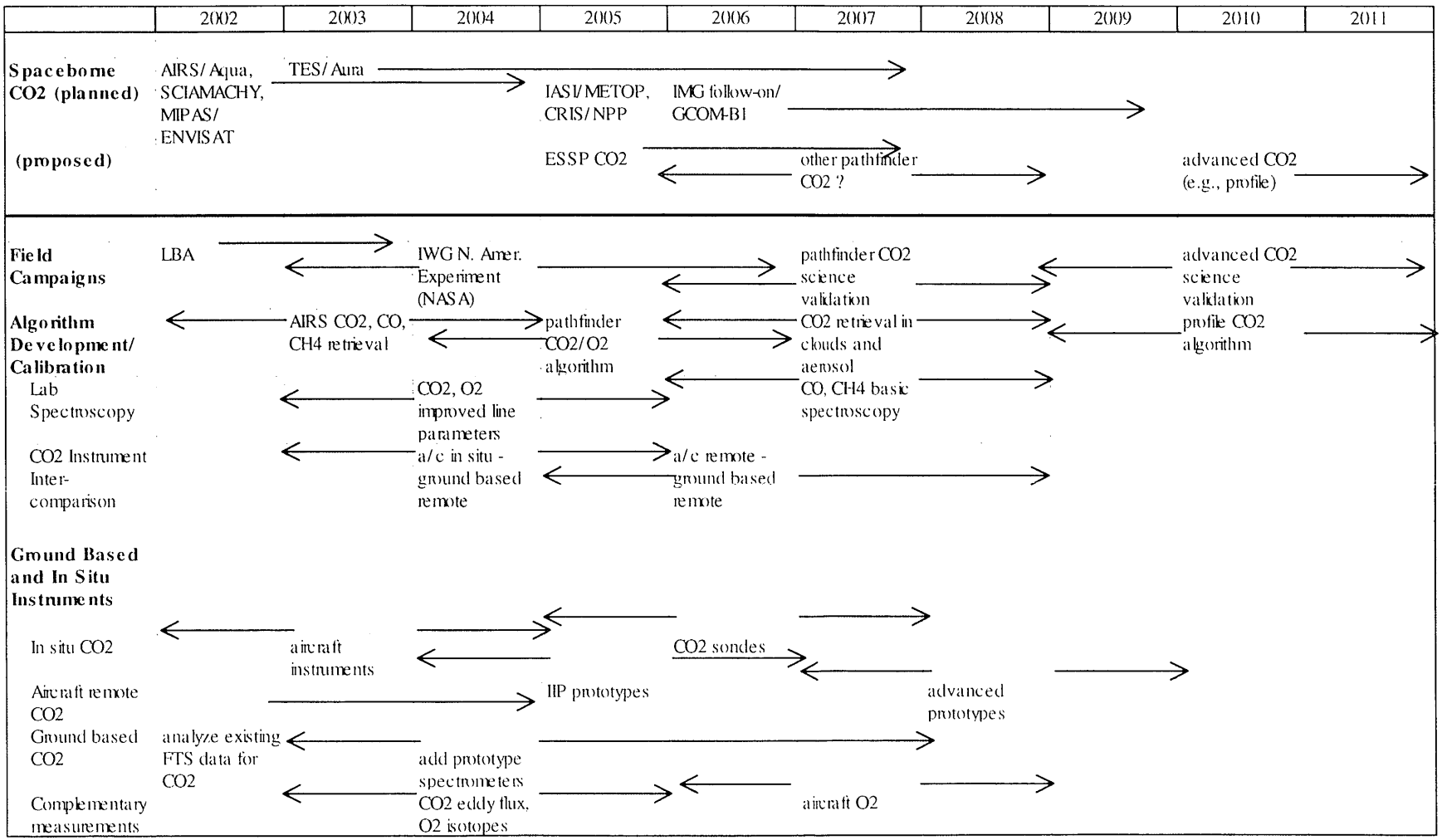
Mission Life: 3 Years

Orbit: 590 km circular sun-synchronous with a 7:00 a.m. or 7:00 p.m. ascending node

Space Access: Delta 2320-10 or equivalent class launch vehicle

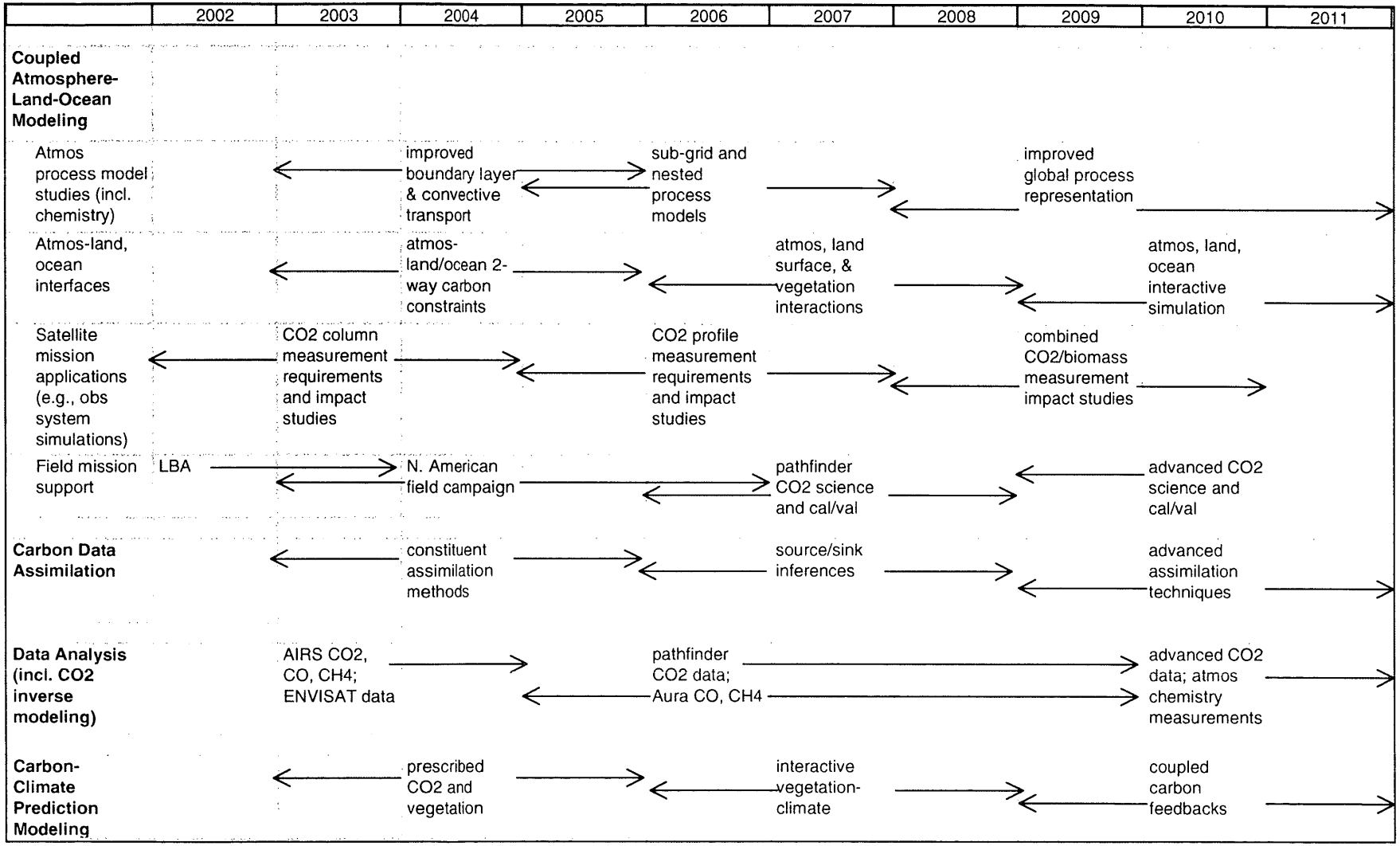
Key Technologies: 1570 nm lidar sensor, S-band low power transceiver

Figure 18a. Atmospheric Carbon Measurement Activities



Note: Arrows are meant to represent peak activity levels over time.

Figure 18b. Atmospheric Carbon Modeling and Data Analysis



Note: Arrows are meant to represent peak activity levels over time.

Figure 19. NASA GCCP Land Activities

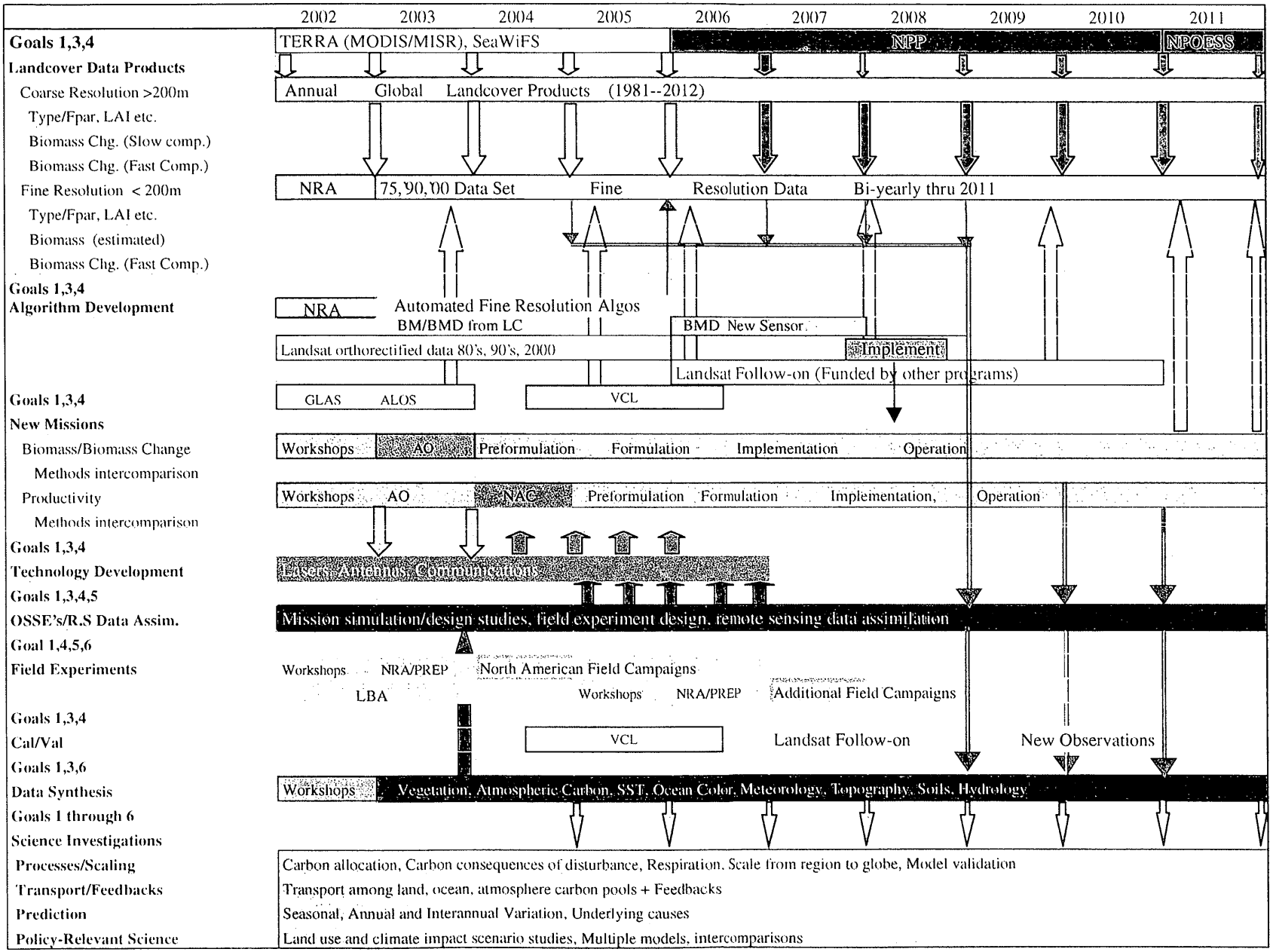


Figure 20. NASA GCCP Ocean Activities

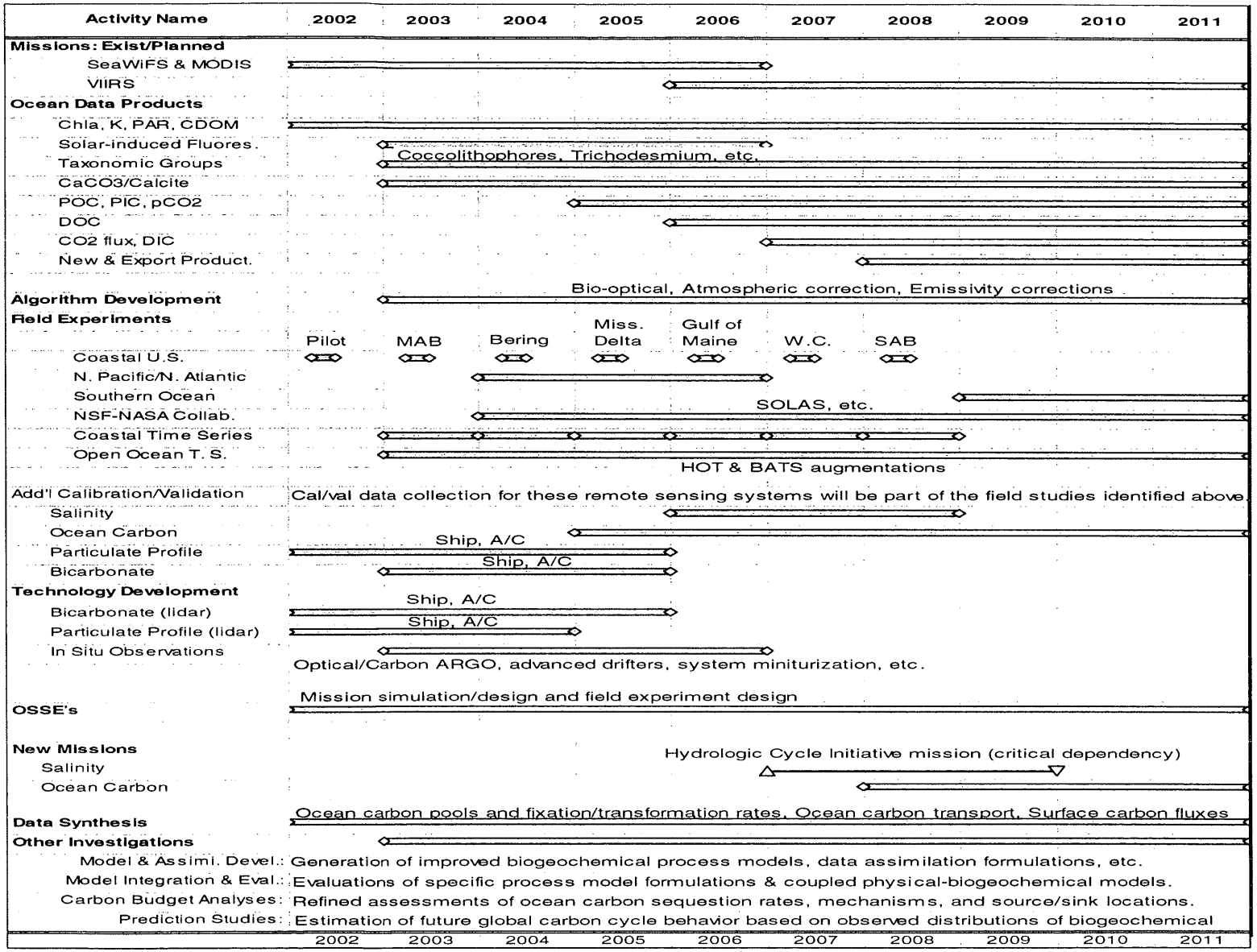


Figure 21. GCCP Interfaces and Functions

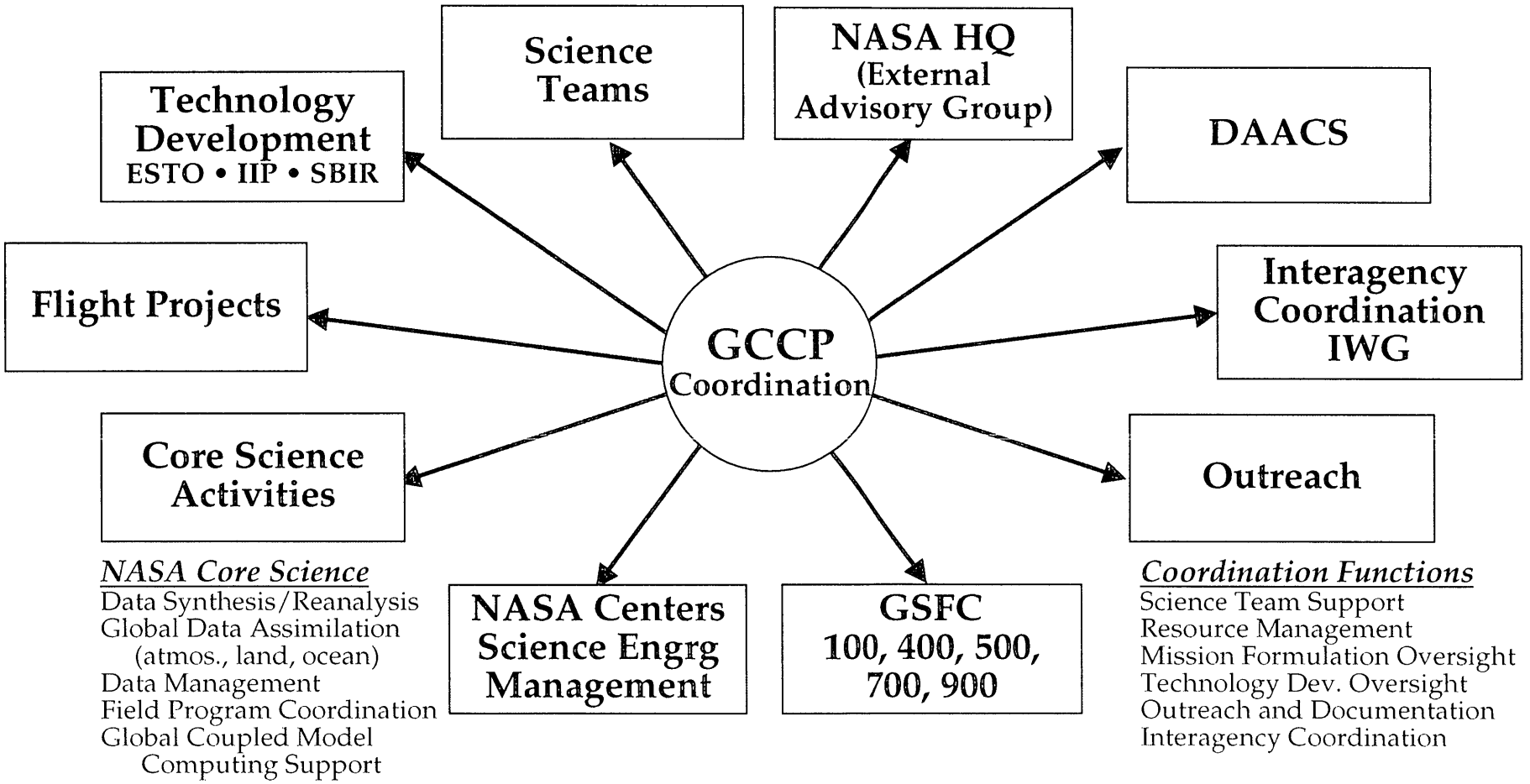
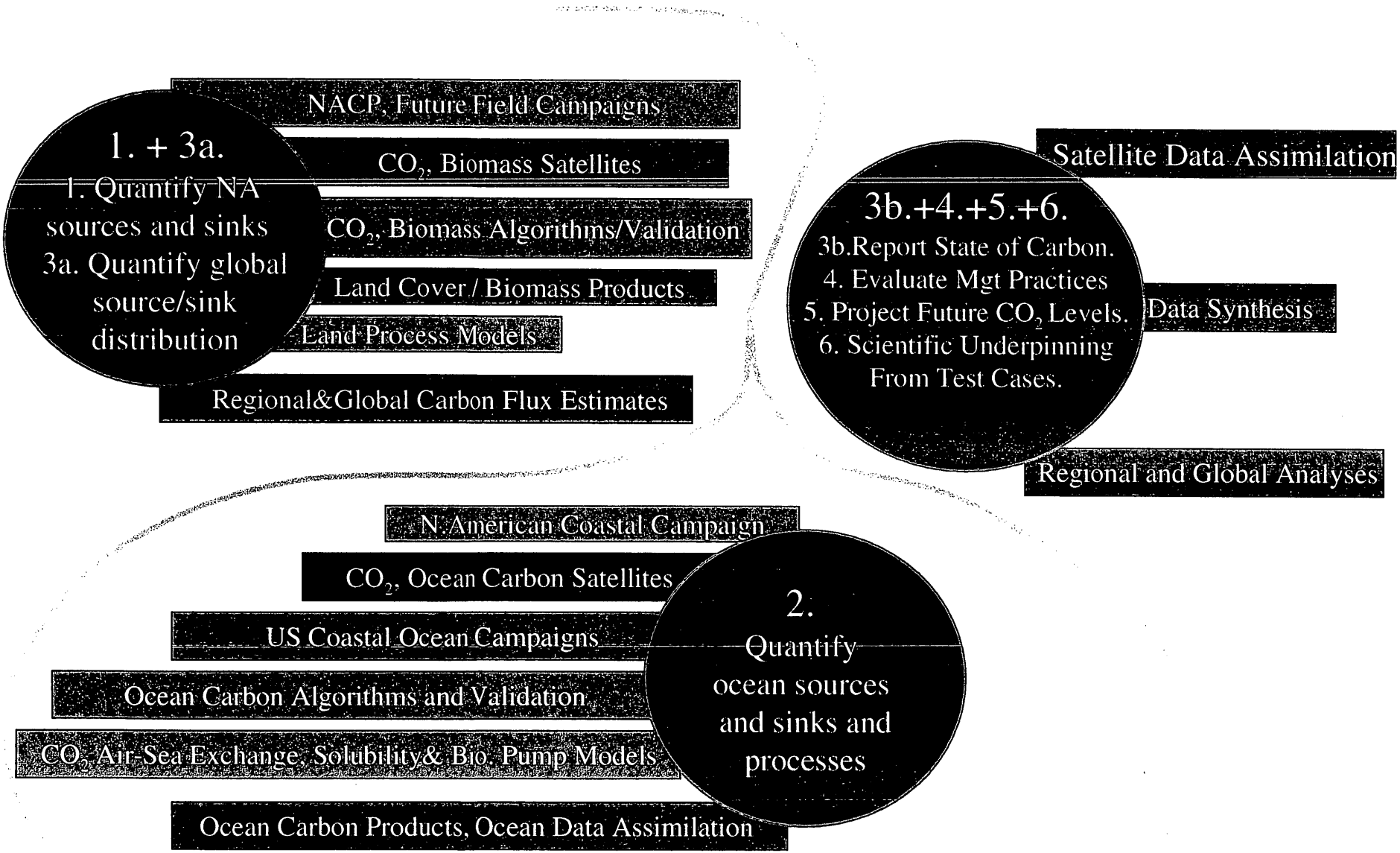


Figure A1.1. USGCRP Goals and Associated Activities



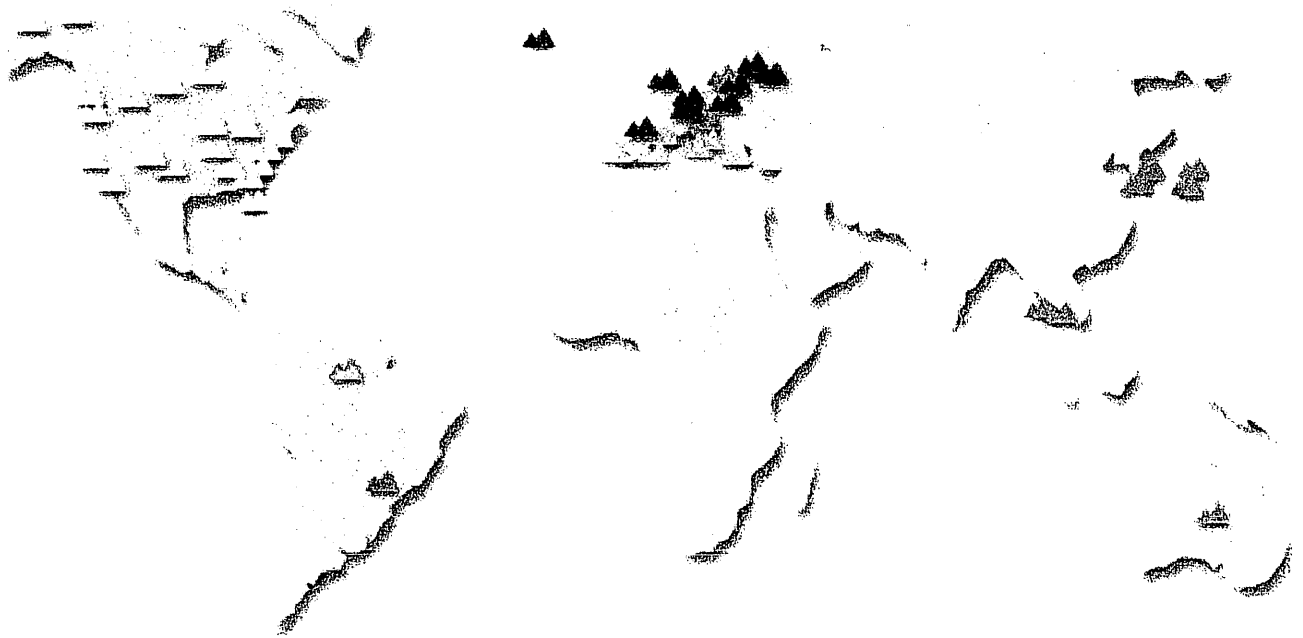


Figure A2.1. Global locations of EOS terrestrial field sites. Yellow are U.S. Long Term Ecological Research (LTER), Ameriflux, and BOREAS sites. Blue, pink, and purple are CarboEurope and Euroflux sites. Red are LBA and other sites. See the EOS land validation webpage (http://modis-land.gsfc.nasa.gov/val/coresite_gen.asp) for details.

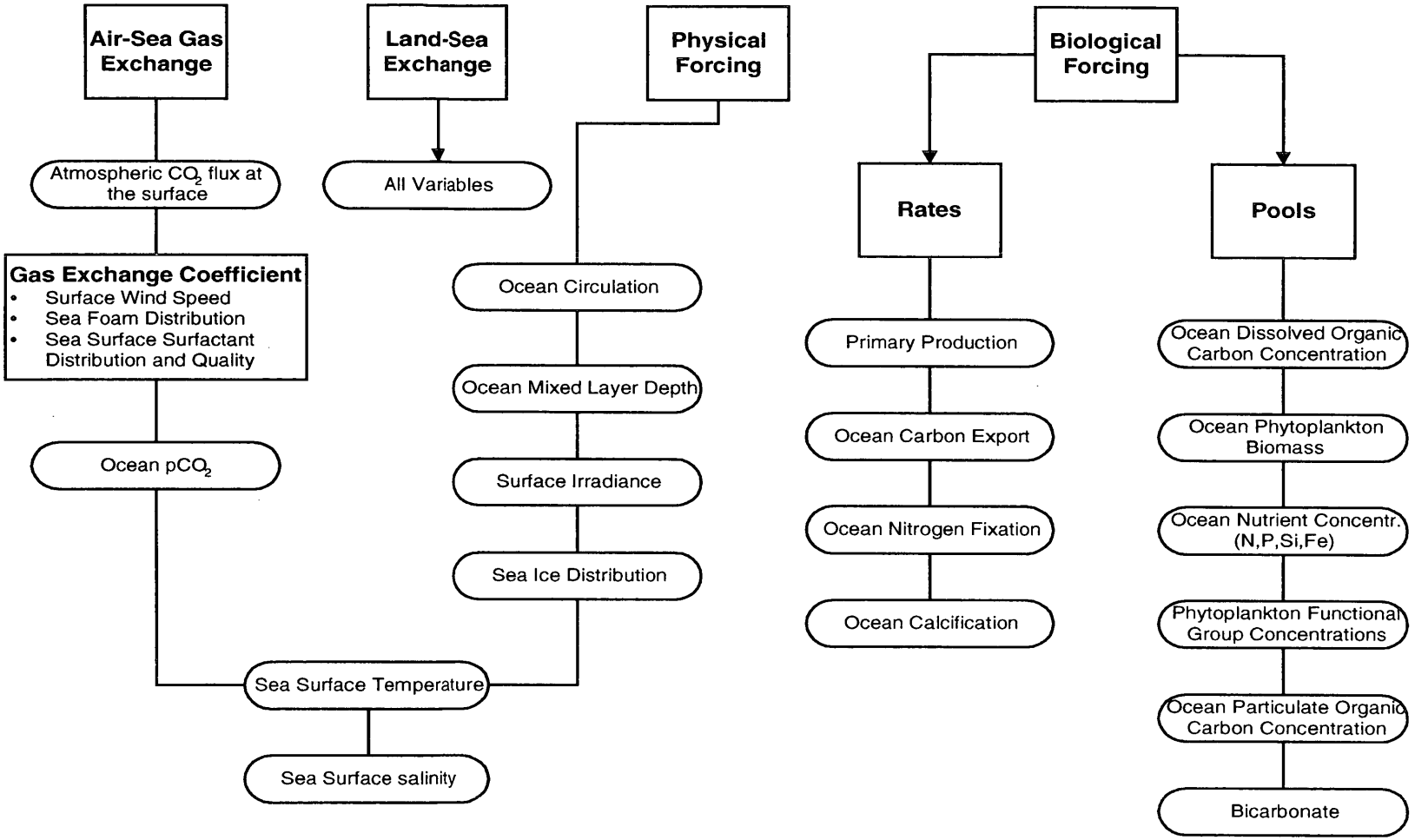


Figure A5.1. Block diagram showing the variables required for estimating the ocean carbon budget and meeting the GCCP objectives.

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13. ABSTRACT *(Maximum 200 words)*
Between October 2000 and June 2001, an Agency-wide planning effort was organized by elements of NASA Goddard Space Flight Center (GSFC) to define future research and technology development activities. This planning effort was conducted at the request of the Associate Administrator of the Office of Earth Science (Code Y), Dr. Ghassem Asrar, at NASA Headquarters (HQ). The primary points of contact were Dr. Mary Cleave, Deputy Associate Administrator for Advanced Planning at NASA HQ and Dr. Charles McClain of the Office of Global Carbon Studies (Code 970.2) at GSFC. During this period, GSFC hosted three workshops to define the science requirements and objectives, the observational and modeling requirements to meet the science objectives, the technology development requirements, and a cost plan for both the science program and new flight projects that will be needed for new observations beyond the present or currently planned. The plan definition process was very intensive as HQ required the final presentation package by mid-June 2001. This deadline was met and the recommendations were ultimately refined and folded into a broader program plan, which also included climate modeling, aerosol observations, and science computing technology development, for contributing to the President's Climate Change Research Initiative. This technical memorandum outlines the process and recommendations made for cross-cutting carbon cycle research as presented in June. A separate NASA document outlines the budget profiles or cost analyses conducted as part of the planning effort.

14. SUBJECT TERMS
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