An Ocean Implementation Plan for the U.S. Carbon Cycle Science Program (CCSP-Oceans)

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A White Paper for the U.S. Carbon Cycle Science Program (CCSP) Scientific Steering Group (SSG) and Inter-agency Working Group (IWG)

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1 Summary

The ocean carbon cycle is a key component of the global climate system, regulating on annual to millennial time-scale the uptake, storage, and release to the atmosphere of carbon dioxide (CO_2) and other climate relevant chemical species. Currently about 30% of the anthropogenic carbon emitted to the atmosphere by fossil-fuel burning is removed by oceanic uptake, but the future behavior of this important carbon sink is quite uncertain because of potential climate change impacts on ocean circulation, biogeochemical cycling, and ecosystem dynamics. A coordinated observational, experimental and modeling research effort is required to address the scope of these ocean carbon problems and their connections to physical climate and other aspects of the global carbon cycle. We present an integrated, multi-agency implementation plan for oceanic monitoring and research aimed at determining how much carbon dioxide is being taken up by the ocean at the present time and how climate change will affect the future behavior of the carbon sink. This plan is the ocean component of the U.S. Carbon Cycle Science Program, **CCSP-Oceans**. It builds on the extensive set of U.S. and international community planning workshops and reports completed over the last several years.

Within the broader goals outlined by the U.S. CCSP, we highlight four fundamental science questions:

1. What is the global inventory, geographic distribution, and temporal evolution of **anthropogenic CO_2** in the oceans?
2. What is the magnitude, spatial pattern, and variability of **air-sea CO_2 flux**?
3. What are the major physical, chemical, and biological **feedback mechanisms** and **climate sensitivities** for ocean carbon storage?
4. What is the scientific basis for ocean carbon **mitigation strategies**?

The implementation strategy consists of the following coordinated elements:

- Enhancing the **global ocean carbon observing network** based on global carbon hydrographic surveys, surface water observations, time-series, satellite remote sensing, and a North American coastal observing system.
- Conducting targeted, **multi-disciplinary process studies** on the response of upper ecosystems and air-sea CO_2 flux to inter-annual climate variability, biogeochemical cycling in the mesopelagic zone, continental margin carbon dynamics, air-sea gas exchange, and Southern Ocean dynamics.
- Integrating field observations, **data synthesis and numerical modeling** through forward prognostic models as well as inverse and data assimilation techniques.
- Accelerating **enabling activities** such as technology development, data management and accessibility, international cooperation, workshops, education and outreach, contributions to national carbon assessments, and ongoing scientific oversight and coordination.

A phased, basin-by-basin approach is proposed for a 10 year program broken into two 5 year components. In phase 1 (beginning in 2003 ramping up to the full program in 2005-2009) emphasis will be placed on the North Atlantic and Pacific in conjunction with the

North American Carbon Program. Southern Ocean synthesis and pilot studies are also proposed for phase 1 followed by a full Southern Ocean field effort in phase 2 (2010-2014). Particular emphasis is placed in phase 1 on accelerating technology development and field testing for new biogeochemical techniques, in situ manipulation experimental approaches, remote sensing algorithms, data assimilation, and autonomous sensors and platforms that have the opportunity to revolutionize how ocean carbon cycle research is conducted and will provide the capability to measure important properties over large sections of the ocean on an almost continual basis.

Anticipated scientific products and payoffs from CCSP-Oceans are summarized as follows:

- Temporal evolution and lateral transport of ocean natural and anthropogenic CO_2, nutrients, oxygen, DOM, and trace metals (e.g., constrain basin-scale decadal changes of anthropogenic carbon inventory to +/- 20%)

- Air-sea CO_2 flux basin-scale to global patterns, seasonal to inter-annual variability, and climate sensitivity (e.g., constrain North Atlantic and North Pacific fluxes to +/-0.2 Pg C/y)

- Seasonal to interannual variability and secular trends for upper ocean carbon cycling, ecosystem structure, primary and export production, and subsurface carbon dynamics

- North American coastal ocean and continental margin air-sea CO_2 fluxes, land-ocean and coastal open ocean carbon exchange, and biogeochemical cycling

- Physical, chemical, and biological controls on present and future marine ecosystems and ocean carbon cycle including biogeochemical responses to and feedbacks on climate change

- New suite of tested in situ, remote sensing and numerical tools for observing and studying the ocean carbon system

- Communication of research findings and decision support tools to stakeholders (scientific community, policy makers, resource managers, students, general public)

2 Introduction

Over the last two centuries, the composition of the Earth's atmosphere has been altered substantially by human activities, including fossil fuel burning, agriculture, deforestation and industrial emissions. The levels of atmospheric carbon dioxide (CO_2), an important greenhouse gas that modulates Earth's radiative balance and climate, have increased from a preindustrial value of 280 ppm to about 370 ppm at present (equivalent to an increase of ~180 Pg of carbon; 1 Pg $=10^{15}$g). A definitive anthropogenic origin for the excess carbon dioxide can be assigned based on contemporaneous changes in carbon isotopes and by the fact that the atmospheric carbon dioxide levels for the preceding several millennia of the Holocene had hovered within plus or minus 5 ppm of the preindustrial value (Prentice et al., 2001). 'Business as usual' economic and climate scenarios project values as high as 700 to 800 ppm by the end of the twenty-first century, levels not experienced on Earth for the past several million years (Pearson and Palmer, 2000).

These human perturbations occur on top of a large, natural carbon cycle background, a complex system involving the ocean, atmosphere and land domains as well as the fluxes between them. The ocean is the largest labile reservoir for carbon on decadal to millennial time scales, acting as a variable sink for atmospheric CO_2 and other climate-relevant trace gases (e.g., Siegenthaler and Sarmiento, 1993), and it will serve as the ultimate sink for about 90% of the anthropogenic carbon released to the atmosphere (Archer et al., 1998). Recent estimates suggest that only about half of the CO_2 released by human activity during the last two decades has remained in the atmosphere; on average, about 30% of the CO_2 emissions or ~2 Pg C/y has been taken up by the ocean (Quay et al., 1992; Takahashi et al., 1999). The future behavior of this ocean carbon sink is uncertain, however, because of possible feedbacks among climate change, ocean circulation, marine biota, and the ocean carbon cycle (e.g., Joos et al., 1999; Bopp et al., 2001).

The U.S. Carbon Cycle Science Plan (Sarmiento and Wofsy, 1999) identifies five overall scientific goals, three of which have significant ocean components:

- Goal 1: Understanding the Northern Hemisphere land sink;
- Goal 2: Understanding the ocean carbon sink;
- Goal 4: Improving projections of future atmospheric CO_2.

Goal 1 requires improved estimates of riverine transport, biogeochemical cycling, and air-sea CO_2 fluxes in adjacent coastal waters and open North Atlantic and North Pacific basins. Goal 2 is intended to establish accurate estimates of the oceanic carbon sink, including interannual variability, spatial distribution, sensitivity to change in climate, and underlying mechanisms. Goal 4 has related objectives that require a mechanistic understanding of biological, chemical, and physical processes that lead to carbon cycle-climate feedbacks. Achieving these goals requires an integrated oceanic program involving strategies for observations over a wide range of temporal and spatial scales combined with experimental studies and model development.

The objective of this white paper is to outline an implementation strategy for the ocean component of the U.S. Carbon Cycle Science Program, ***CCSP-Oceans***. An Interim Implementation Group was formed in July, 2002 by the U.S. CCSP Scientific Steering Group and Inter-agency Working Group. The specific charge to this group is to develop integrated, cross-agency implementation ideas; facilitate implementation and coordination of existing and emerging U.S. ocean carbon cycle research; and maintain links to other components of the U.S. CCSP, climate and ocean physics, and international programs.

This white paper draws heavily on a series of U.S. and international ocean carbon cycle community meetings, workshops and planning reports completed over the last several years. These include in particular: OCTET-Ocean Carbon Transport, Exchanges and Transformation (Lee et al., 2000); EDOCC-Ecological Determinants of the Ocean Carbon Cycle (reference, 2000); U.S. SOLAS-Surface Ocean Lower Atmosphere Study (Wanninkhof, 2002); LSCOP-Large-scale CO_2 Observing Plan (Bender et al., 2002); an international GOOS-Global Ocean Observing System report on ocean carbon (Doney and Hood, 2002); the RioMar report (McKee et al., 2003); and a series of U.S. JGOFS Synthesis and Modeling Project workshops and reports. The reports document in detail the current state of our understanding of the ocean carbon cycle, the critical knowledge gaps and outstanding research questions, and the rationale for a coordinated research program. Here we focus on presenting the corresponding implementation structure.

The global carbon cycle is a single system with multi-faceted aspects cutting across the three major domains: the ocean, land, and atmosphere. Many of the most important advances in the field over the last decade involve combining data sets and models for the different reservoirs in new ways because results from one domain often place invaluable constraints on the workings of the other two. For example, the complexity and variability of carbon storage and uptake on land suggests that the long-standing approach of separately determining storage and fluxes in the ocean and atmosphere and evaluating regional and global behavior of the terrestrial biosphere by difference will likely be required well into the future. This report acknowledges the global nature of the carbon cycle but addresses only the ocean component and relevant ocean-atmosphere and land-ocean interactions. The recommendations, however, have been coordinated closely with the implementation documents for the U.S. CCSP North American Carbon Program (NCAP) (Wofsy and Harriss, 2001; Wofsy et al., 2003) and the Carbon Data Assimilation initiative (Fung et al., 2003).

3 Science Background

The fossil fuel carbon source and growth of atmospheric CO_2 are reasonably well known based on economic reconstructions and atmospheric monitoring (Prentice et al., 2001). A number of complementary, albeit indirect, means have been proposed for partitioning the long-term net carbon sink between ocean and land reservoirs, producing generally similar results for the global net ocean uptake of ~2 Pg C/y. These include global ^{13}C budgets for CO_2 (Quay et al., 1992; Tans et al., 1993; Heimann and Maier Reimer, 1996; Quay et al., 2003) data based estimates of anthropogenic CO_2 inventories in the ocean (Gruber et al., 1996, Sabine et al., 1999, Sabine et al., 2002), ocean forward and inverse models (Sarmiento et al., 2001; Gloor et al., 2002), and combined use of atmospheric oxygen and CO_2 records (Keeling and Shertz, 1992, Keeling et al., 1996). Given the significant uncertainties that are associated with each of these indirect methods, it is imperative to document the time evolution of the oceanic carbon inventory directly through repeat measurements. The regional air-sea flux patterns are less well known, with significant disagreement among atmospheric inversions, ocean surface pCO_2 flux estimates and ocean numerical models particularly for the North Atlantic and Southern Ocean (Takahashi et al., 2002; Gurney et al., 2002). The 1990's WOCE/JGOFS global survey provides a high quality/precision baseline estimate of the ocean dissolved inorganic carbon (DIC) distribution, and preliminary direct estimates of the ocean DIC temporal evolution and horizontal ocean DIC transport are being developed (Wallace, 2001).

The net ocean uptake of anthropogenic carbon appears to be controlled over the historical period and at present by ocean physics, namely the ventilation and exchange of surface waters with the thermocline and intermediate/ deep waters (Sarmiento and Gruber, 2002). This uptake, however, is superimposed upon the large background inventory and spatial and temporal gradients of DIC within the ocean driven by the natural marine carbon cycle. These patterns include substantial net CO_2 outgassing at the equator and ingassing at high latitudes governed by the physical solubility pump and the particulate organic and inorganic and dissolved organic matter biological pumps (Takahashi et al., 2002). At high latitudes the solubility of CO_2 in water, as well as the density of seawater, increases due to decreasing temperatures. As the cooled surface water sinks to depth it enhances the storage of CO_2 in deep ocean waters, the so-called solubility pump. Alternatively, the biological pump refers to the processes that convert CO_2 to organic and inorganic matter by photosynthesis and remove the carbon to depth (where it is respired or remineralized) via sinking particles, diffusion, physical mixing, and active transport. In many ocean regions the biological pump can have a stronger control on the distribution of CO_2 than the solubility pump. Furthermore, present models predict that without a biological pump the atmospheric CO_2 concentration would rise to levels of ~680 ppm, about 400 ppm above pre-industrial levels.

Intensive field research over the last two decades (Fasham et al., 2001) and recent availability of satellite ocean color measurements (McClain et al., 1998; 2002) have greatly improved our understanding on the seasonal and geographical patterns of particulate carbon export flux from the upper ocean, phytoplankton standing stock, and marine primary productivity. There is also a growing appreciation of the complexity of factors governing the ocean biological pumps (e.g., iron limitation, nitrogen fixation, calcification, community structure, mesoscale physical-biological interaction, subsurface remineralization).

The limited number of long-term ocean time series stations show significant biogeochemical variability from sub-diurnal to decadal timescales. Changes in large-scale ocean-atmosphere patterns such as ENSO, the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO) appear to drive much of the inter-annual variability, and this variability is expressed on regional (several hundred-to-thousands of kilometers) rather than basin-to-global scales. Large inter-annual variability in the partial pressure of surface water CO_2 (pCO_2) and CO_2 fluxes in the Equatorial Pacific are well documented (Feely et al., 1999b; 2002). Mid-latitude variability signals are less clear (LeQuere et al, 2000; in press). But at the Bermuda Atlantic Time-Series Station (BATS), a clear correlation has been demonstrated between NAO and ocean hydrographic and biogeochemical variables such as temperature, mixed layer depth, primary production, and total DIC, suggesting that the North Atlantic is likely responding in a coordinated, basin-wide manner to interannual variability (Bates, 2001; Gruber et al. 2002; Bates et al., 2002). This is in agreement with modeling studies (Williams et al., 2000; McKinley et al., 2000), which also found that variations in heat fluxes and wind stirring leading to variations in winter time mixed layer depths are the main drivers for inter-annual variability in export production and seasonal oxygen fluxes.

The slower, decadal time-scale ocean responses (e.g., changes in nutrient stocks and community structure) are not as well characterized as the interannual response, though there is tantalizing evidence for large-scale biogeochemical regime shifts (or perhaps secular trends) (Karl, 1999) and changes in nutrient distributions (Emerson et al., 2001). Distinguishing a human-induced, climate-change signal from natural decadal variability on this time-scale is often singularly difficult, particularly given the relatively short duration of most oceanographic data records. But model projections suggest that anthropogenic impacts are accelerating and become more evident in the near future.

Under future greenhouse warming climate scenarios, the physical uptake of anthropogenic carbon by the ocean is expected to decline because of surface warming, increased vertical stratification, and slowed thermohaline circulation (Sarmiento et al., 1998; Matear and Hirst, 1999). In coupled simulations with simple biogeochemical models, these physical effects are partly compensated by increased uptake from changes in the strength of the natural biological carbon pump. The biogeochemical response is governed by two opposing factors, a reduction in the upward nutrient supply due to the increased stratification, which leads to decreased export production of organic matter and carbon dioxide uptake, and a decrease in the upward vertical flux of dissolved inorganic carbon. The latter factor generally dominates in the present simulations, so that the effect of altered biogeochemistry is a net positive carbon dioxide uptake. Given the low level of biological sophistication used in these early simulations, such projections must be considered preliminary, demonstrating the potential sensitivity of the system and posing important questions to be addressed through future research.

A wide variety of other mechanisms have been identified that could conceivably alter ocean carbon uptake, but in many cases even the sign of the biogeochemical response, let alone the quantitative magnitude, is uncertain (Denman *et a*l., 1996; Doney and Sarmiento, 1999). Potential effects include:

- decreased calcification from lower pH and CO_3 ion concentrations resulting from anthropogenic CO_2 uptake (Kleypas et al., 1999; Riesebell et al., 2000);
- decreased vertical nutrient supply and in some regions enhanced, effective-surface-layer light supply leading to often opposing regional changes in primary productivity (Bopp et al., 2001);
- alterations in the spatial patterns and community composition of marine biomes due to changes in stratification (Boyd and Doney, 2002);
- modifications in dust deposition and iron fertilization affecting the high nitrate-low chlorophyll (HNLC) regions such as the Southern Ocean and possibly subtropical nitrogen fixation;
- decoupling of carbon and macronutrient cycling because of shifts in the elemental stochiometry of surface export and differential subsurface remineralization.

Accounting for such hypotheses in future climate projections is presently problematic given our current understanding and modeling tools (Doney, 1999; Falkowski et al., 2000).

A number of technological strategies have been proposed for mitigation of atmospheric CO_2 build-up via deliberate carbon sequestration. One marine approach involves capturing fossil-fuel carbon locally at production or combustion sites and then injecting it directly into the deep-ocean (e.g., Brewer et al., 1999). Other methods involve enhancing biological carbon uptake and storage from ocean ecosystems through deliberate nutrient fertilization. The most commonly proposed approach is based on the assertion that phytoplankton in the surface layer of high-nitrate low chlorophyll (HNLC) regions are iron limited (e.g., Coale et al., 1996). In considering mitigation strategies, societies must assess the desired atmospheric CO_2 targets, the economic trade-offs between reducing fossil-fuel use versus deliberate sequestration, the feasibility of the sequestration strategy, the environmental consequences, and the capability to maintain such efforts over long time periods (Dilling et al., submitted).

Many basic aspects of the ocean carbon system are inadequately understood, directly impacting our ability to make realistic future projections and or assess potential carbon management scenarios. Areas requiring particular focus include the mechanistic controls on upper ocean ecosystem structure and the elemental composition of export fluxes; the dynamics of organic and inorganic transport and remineralization in the mesopelagic zone; land-ocean exchange and carbon cycling in the coastal ocean and along continental margins; and the mechanisms of air-sea gas exchange. Recent advances on new biogeochemical techniques (e.g., molecular probes, eddy correlation CO_2 fluxes) and large-scale ocean experimental manipulation (e.g., iron fertilization) suggest that an opportunity exists at present to make rapid progress in these areas. Technological developments involving autonomous instruments, remote sensing and numerical modeling also give us for the first time a real prospect that we will be able to measure important properties over large sections of the ocean on an almost continual basis.

Therefore the acceleration of the development and field validation of such is instruments and techniques is highlighted as a key program element in the proposed phase 1 of CCSP-Oceans.

4 Objectives and Implementation Strategy

While the overarching CCSP goals described in section 2 (Sarmiento and Wofsy, 1999) provide general guidance for the development of a CCSP-Oceans program, more focused scientific questions must be articulated in order to design a research implementation plan. A major common theme that runs through community ocean carbon planning documents is constraining the past, present and future net oceanic uptake rate of CO_2. To accomplish this task, one must have a good quantitative description of the modern carbon cycle (inventory, air-sea fluxes, and internal cycling) and be able to quantify and attribute historical perturbations. Further, one must have a good mechanistic understanding of the main physical, chemical, and biological mediated processes governing carbon cycling and how those processes would respond to warming, stratification and other climate change factors as well as the potential for direct carbon mitigation. Climate sensitivity can be expressed in terms of changes in the ocean's capacity to absorb atmospheric CO_2, providing a common framework for examining a wide range of processes regulating carbon fluxes in the oceans and leading directly to more reliable projections of the future trajectory of atmospheric CO_2. This vision is outlined below in more detail through a set of four fundamental questions that guide the development of the implementation strategy.

1) What is the global inventory, geographic distribution, and temporal evolution of anthropogenic CO_2 in the oceans?

The WOCE/JGOFS global CO_2 survey results provide the first global snapshot of the ocean inorganic carbon inventory and partitioning into pre-industrial and anthropogenic components. Major tasks now include observing directly the temporal evolution of the fields of inorganic carbon and other biogeochemically relevant species (e.g., nutrients, oxygen, trace metals, dissolved organic matter); measuring the response of those fields to increased warming, stratification, and slowed thermohaline circulation; and reconciling net carbon uptake estimates and spatial patterns derived from different methods (e.g., empirical in-situ techniques; air-sea fluxes; temporal evolution; atmospheric CO_2 and O_2/N_2 constraints; $\delta^{13}C$ isotopic composition; existing and new transient tracer proxies; and forward and inverse models).

2) What is the magnitude, spatial pattern, and variability of air-sea CO_2 flux?

A general picture of the large-scale, climatological pattern and seasonal cycle of air-sea CO_2 flux can be derived at present from historical surface water pCO_2 transect data and empirical wind speed gas exchange relationships. The current major challenges are improving the understanding of the biological and physical processes driving air-sea fluxes; quantifying the interannual to decadal variability; assessing the significant regional differences (e.g., Southern Ocean) between in-situ and atmospheric inverse derived fluxes; estimating air-sea fluxes over the continental margins and their imprint on atmospheric CO_2 over the continents; and reducing the large (+/- 50%) uncertainty in air-sea gas exchange parameterizations by characterizing at a basic, mechanistic level the physical, chemical and biological controls on air-sea gas exchange.

3) What are the major feedback mechanisms and climate sensitivities for ocean carbon storage?

Climate projections over the next several centuries show substantial ocean surface warming, enhanced vertical stratification, and altered physical circulation, all of which suggest reduced ocean carbon uptake. Significant changes in the areal extent and community composition of marine biomes are also suggested, and the structure of marine ecosystems directly influences the flow of carbon between trophic levels and, ultimately, the partitioning of CO_2 between the atmosphere and the deep sea. Also relevant are global change factors such as changes in the carbonate system (reduced ocean pH and carbonate ion) and alterations in atmospheric dust deposition. Marine biogeochemical responses and feedbacks to such perturbations, however, are poorly characterized at present, and basic, mechanistic research is needed on the climate sensitivities and feedbacks to atmospheric CO_2 of, for example: efficiency of surface water nutrient utilization; nitrogen fixation, denitrification, and the oceanic inventory of fixed nitrogen; elemental ratios (e.g., C/N/P) and carbonate to organic carbon ratio of exported biogenic material; regeneration length scales and differential elemental remineralization for biogenic material; and community allocation of fixed carbon into particulate versus dissolved organic matter pools. Specific research questions include delineating the physical, chemical and biological factors governing present biogeochemical cycling and future responses.

4) What is the scientific basis for ocean carbon mitigation strategies?

A number of oceanic carbon mitigation approaches for enhancing ocean carbon sequestration have been proposed including direct CO_2 injection and ecosystem manipulations such as iron fertilization of high-nitrate low chlorophyll zones or nitrogen fixing subtropical gyres. The scientific bases for these technological strategies, however, are not fully developed, and more through understanding of the feasibility, overall climate effectiveness, environmental impacts, stability and sequestration time scales are needed.

The overall implementation strategy described in the following sections involves a coordinated program for:

- Enhancing the **global ocean carbon observing network** based on global carbon hydrographic surveys, surface water transects, time-series, satellite remote sensing, and a North American coastal observing system.
- Conducting targeted, **multi-disciplinary process studies** on the response of upper ecosystems and air-sea CO_2 flux to inter-annual climate variability, biogeochemical cycling in the mesopelagic zone, coastal ocean carbon dynamics, air-sea gas exchange, and Southern Ocean dynamics.
- Integrating **field observations, data synthesis and numerical modeling** through forward prognostic models as well as inverse and data assimilation techniques.

- Accelerating **enabling activities** such as technology development, data management and accessibility, international cooperation, workshops, education and outreach, contributions to national carbon assessments, and ongoing scientific oversight and coordination.

A phased, basin-by-basin approach is proposed for a 10 year program broken into two 5 year components. In phase 1 (beginning 2003 ramping up to the full program in 2005-2009) emphasis will be placed on the North Atlantic and Pacific in conjunction with the North American Carbon Program. Southern Ocean synthesis and pilot studies are also proposed for phase 1 followed by a full Southern Ocean field effort in phase 2 (2010-2014).

A number of the observing system components have recently been funded and are already underway. The prioritization for implementing other specific elements of the program is based on an assessment of the expected impact of particular processes on ocean carbon storage, the relative uncertainty and limits of current understanding, the ability to leverage and build on ongoing and emerging field components, and the readiness of the technology and scientific infractructure. Wherever possible, sample design is developed using quantitative metrics. Each of the following implementation sections includes brief background and rationale, overview of existing and planned field/modeling components, specific recommendations for new research on the near to mid-term (CCSP-Oceans phase 1), and requirements for national and international integration and coordination.

5 Ocean Carbon Observing System

The development of a unified, global ocean carbon observing system is fundamental to addressing the four CCSP-Oceans science questions detailed in Section 4. With a few exceptions (e.g., WOCE/JGOFS global carbon survey; JGOFS HOT and BATS time-series stations), most past ocean carbon sampling efforts have been conducted in a research mode characterized by a small number of principal investigators, limited scope and duration. This independent research path provides many of the scientific insights and advances in ocean carbon research and will continue as an important element of CCSP-Oceans (Section 6). Ocean observing systems are emerging in a number of oceanographic contexts (Fine et al., 2001; Doney and Hood, 2002; Bender et al., 2002), and the key attributes that distinguish such systems include: basin to global extent; decadal or longer temporal duration; careful attention to internal data consistency and long-term biases; timely public release of data products; and coordination at national and international levels (see Section 8 on enabling activities).

No single measurement technique or approach can encompass the wide range of relevant time and space scales and processes of the ocean carbon cycle. A major challenge in observing system design, therefore, is to integrate the diverse suite of ship based, autonomous, and remote sensing observations detailed below. While data synthesis and numerical modeling will play an important role (Section 7), careful consideration of the various different, but complementary, measurement approaches is needed from the start. The observing system described below attempts to take advantage of synergies across the different components (e.g., tying repeat hydrographic lines into a long-term time-series network) and stresses the utilization of common standards, reference materials, uniform measurement techniques, and inter-comparison exercises wherever possible.

Traditional shipboard oceanographic surveys remain a key necessary element of the proposed sampling strategy, providing continuity with historical data and the capability for full-water-column sampling, accurate high-precision laboratory measurements, and detailed, intensive process studies. Clearly, however, this method is insufficient for the high spatial and temporal sampling frequencies required for many ocean carbon issues. Following the lead of the physical oceanographic community, marine biogeochemists need to capitalize on emerging *in situ* autonomous measurement / sampling technologies in order to sample the ocean chemical and biological state over the appropriate range of scales (Section 8.1). The rapid evolution and eventual outcome of these technological developments, however, are difficult to foresee. The detailed planning and optimization of the global monitoring system must include enough flexibility to account for the fact that many revolutionary techniques may be developed in the coming years. The vantage point of space-borne sensors provides almost optimal conditions for monitoring. It also offers a data density that is well suited to force, constrain, and assimilate into models. Efforts should also be made to improving the understanding and parameterization of key processes within the carbon cycle. There exist clear limitations to remote sensing, such as resolution and the suite of measurable variables, but at the very least, the present set of earth-viewing sensors provides oceanographic and atmospheric context, which will improve as new sensors are launched, such as sea surface salinity and total atmospheric column CO_2.

Ocean Carbon Observing System Elements

- A series of repeat ocean transects, involving reoccupation of selected meridional and zonal WOCE lines, in which CO_2 system properties will be measured along with hydrographic properties, nutrients, transient tracers, and trace metals. Water samples will be collected for post-cruise analyses of pigment concentrations, dissolved organic carbon (DOC), and ^{13}C of inorganic carbon. Programs using AC-9 transmisometers will provide estimates of particulate organic stocks and distribution.

- A comprehensive observing system of pCO_2 distributions and air-sea CO_2 fluxes onboard research and volunteering observing ships (VOS) to extend our understanding of the interannual variability of carbon fluxes and its anthropogenic perturbations. These measurements can be made using autonomous systems requiring little crew support. Bottle samples should be collected for selected properties (e.g. DIC-13C, nitrate) and other underway measurements (e.g., fluorometry) should be conducted where possible.

- Time series stations which are occupied at monthly to seasonal timescales. The measurement suite would include the same properties as those of the repeat ocean transects, plus other measurements which are not easily accommodated on the transects, e.g., primary production.

- Coastal time series stations and seasonal surveys to determine the amounts and pathways of carbon sources and sinks in the continental shelf regions of North America.

- Remote sensing observations of the global patterns and time/space variability of apparent and inherent optical properties, surface water particulate organic and inorganic carbon content, bulk and skin SST, wind speed and gas exchange rates, and aerosol optical properties. The effort will focus on algorithm development for constraining air-sea CO2 flux and biological state variables and rates and application of existing and planned satellite measurements as well as additional aircraft observations.

- Concurrent and historical compilation of variables accessible by remote sensing for existing time series stations, VOS lines, and transects to provide large scale spatio-temporal context and expand the measurement suite. Compilation of global maps of variables accessible by remote sensing, both concurrent and historical to understand and document modes of variability.

Anticipated Scientific Advances

We expect the results of the CCSP-Oceans ocean carbon observing system to provide the following information and scientific products:

- The evolving distribution of both natural and anthropogenic CO_2 and biogeochemically relevant species (nutrients, oxygen, trace metals) in the ocean interior and a more accurate inventory of the DOM pool. Meridional ocean sections, supplemented by zonal lines and time series, will give this information. The evolving time-dependent CO_2 distribution reflects the sum of oceanic processes and is therefore a first order constraint on models used to predict ocean CO_2 uptake.

- Transport of carbon including inorganic and organic carbon and biogeochemically relevant species in the ocean interior. Zonal lines provide the primary constraints on meridional transport of natural and anthropogenic CO_2. Patterns of transport reflect processes of uptake and redistribution.

- Interannual and decadal variability in the oceanic distribution of CO_2, primary production, and biogeochemically relevant species. There is evidence that oceanic ventilation and rates of biogeochemical processes vary during events such as the Pacific Decadal Oscillation, the North Atlantic Oscillation, and the El Niño-Southern Oscillation. Understanding these variations will allow us to document the influence of interannual and decadal variability on ocean uptake of fossil CO_2, and the governing processes.

- Improved constraints on global air-sea CO_2 fluxes and temporal variability of the fluxes. The interior CO_2 fluxes depend, in part, on basin scale uptake rates of anthropogenic CO_2. The data thus give a rate that can be compared with air-sea CO_2

fluxes measured by sea surface studies. They also give a critical independent constraint for inverse calculations of CO_2 uptake by the land biosphere.

- Improved estimates of terrestrial carbon fluxes onto the continental shelves, production of organic carbon within margin systems, and the ultimate fate of this carbon (e.g., deposition, exchange with the open ocean, remineralization to CO_2 and loss to the atmosphere). It has been suggested that a significant fraction of the terrestrial flux may be unaccounted for in current carbon budgets.

- Improved constraints on coupled ocean circulation-biogeochemical models. The information listed above is critical for the validation of ocean biogeochemical models used for predicting future carbon distributions and fluxes, and for reconciling inverse model estimates of sources and sinks with the coupled process models.

5.1 Large Scale Ocean Repeat Hydrographic Survey

The overarching goal of the repeat survey is to determine the large-scale decadal evolution of the anthropogenic CO_2 inventory to within 20% on a global and basin scale (Bender et al., 2002). This goal is greatly aided by the fact that, for the first time, we have a global, high-quality baseline data set of ocean tracer and carbon system observations in the 1990s as part of the World Ocean Circulation Experiment/Joint Global Ocean Flux Study (WOCE/JGOFS). Dissolved inorganic carbon data sets accurate to 2 to 3 μmol/kg, which are equivalent to 2 to 3 years' uptake of anthropogenic CO_2 in near-surface waters, are now available for hydrographic transects representing most of the world's ocean (Gruber et al., 1996; Gruber, 1998; Feely et al., 1999; 2001; Sabine et al., 1999; 2002; Wanninkhof et al., 1999). These high-quality data, when compared with older data of much lesser quantity and quality such as those obtained during the GEOSECS program, have already yielded substantial insight into the carbon inventory changes over time. For example, Sabine et al. (1999) and Peng et al. (1999) reported significant changes in the carbon inventory in the Indian Ocean over the ~18 year interval between GEOSECS and WOCE and were also able to show that these changes agreed well with the expected changes on the basis of ocean ventilation and the rate of increase in atmospheric CO_2. Because of the much higher precision and accuracy of the new carbon data and the fact that atmospheric CO_2 continues to increase rapidly, it is now possible to detect long-term changes in the carbon inventories over time-scales of 10 years and even less.

Methodological advances in DOC analyses over the past 10 years have resulted in an analytical precision of 1 μmol/kg. This improved precision together with the use of DOC reference materials helps to assure detection of long-term trends in temporal and spatial variability of oceanic DOC stocks. For example, small (14 μmol C/kg) but systematic large-scale water column differences have been measured between the Atlantic and Pacific Oceans (Hansell and Carlson, 1998). These data point to differences in DOC input, storage and remineralization patterns in the interior of the respective ocean basins. However, these observations were based on a limited DOC data set and DOC global scale distribution remains weakly resolved. The repeat hydrographic survey will serve to improve our understanding of DOC inventories, large-scale DOC production and remineralization patterns, and its potential contribution to CO_2 variability in the ocean.

Table 1. Provisional CO_2 CLIVAR Repeat Hydrography Schedule, US Lines

Year	Year of Project	Cruise	Days	Ports	Dates	Contact/Chief Scientist
Overall Coordinator: Jim Swift, SIO						
2003	1	A16N	42	Reykjavik-Fortaleza	6/2/03-7/31/03	Bullister, PMEL
2003	2	A20	29	WHOI - Port Of Spain	9/27/03-10/23/03	Toole, WHOI
2003	2	A22	21	Port Of Spain - WHOI	10/26/03-11/22/03	Joyce, WHOI
2004	2	P2	66	San Diego-Honolulu-Yokohama	Summer 2004	
2005	3	A16S	44	Montevideo-Fortaleza Brazil	Austral summer 2005	
2005	3	P16S	40	Wellington-Tahiti	Austral summer 2005	
2006	4	P16N	57	Tahiti-Alaska		
2007	5	S4P	51	Wellington-Perth		
2008	6	P18	32	Punta Arenas-Easter Island		
2008	6		35	Easter Island- San Diego		
2008	6	I6S	42	Cape Town		
2009	7	17N	47			
2009	7	I8S	38			
2009	7	I9N	34			

The NSF/NOAA-sponsored Repeat Hydrography Program has been funded for the period 2003-2008. The program includes a set of the hydrographic sections (shown in Table 1 and Fig. 1), most of them repeats of WOCE Hydrographic Program sections, which will be reoccupied at time intervals of between 5 and 12 years to provide broad-scale global coverage. The measurement suite will include dissolved inorganic carbon (DIC), total alkalinity (TA) and, on some lines, include the two other CO_2-system parameters, pH and pCO_2 to assure internal consistency. Other measurements will include ^{13}C (not currently supported), TOC (total organic carbon) and total organic nitrogen (TON). Standards will be used for measurement of all parameters. In addition to the hydrographic (including: temperature, salinity, oxygen, nutrients, LADCP) and carbon system parameters (DIC, pCO_2 Talk, pH, TOC and TON), transient tracers (i.e., $^3H/^3He$, ^{14}C, $^{13}C/^{12}C$, CFCs, CCl_4 and HFCs) will be measured on these sections to estimate transport fluxes, provide water mass ages, and document changes in these anthropogenic tracers. These measurements are critical to interpret to natural and anthropogenic changes to ocean carbon concentrations. Some of these tracers reveal mixing over the critical longer time scales; and some help identify current short-term invasion rates for comparison with older data. Trace metals, including Fe and Zn, and bio-optical parameters will also be measured in the upper water column. Station spacing on the proposed sections will be eddy-resolving to avoid aliasing of eddies and other variability into the climate signal. By compiling historical and remote sensing data along the section lines, we will be able to enhance our understanding of the spatial and temporal context under which the shipboard measurements are being made. By compiling historical remote sensing data along the sections, we can optimize sampling design. Likewise obtaining real-time snapshots from space during the section enhances our understanding of the spatial and temporal context under which the ship-based measurements are being made. An intensive coordination of satellite and in situ approaches is instrumental to improve our understanding of the patterns and variability of oceanographic and carbon cycle variables.

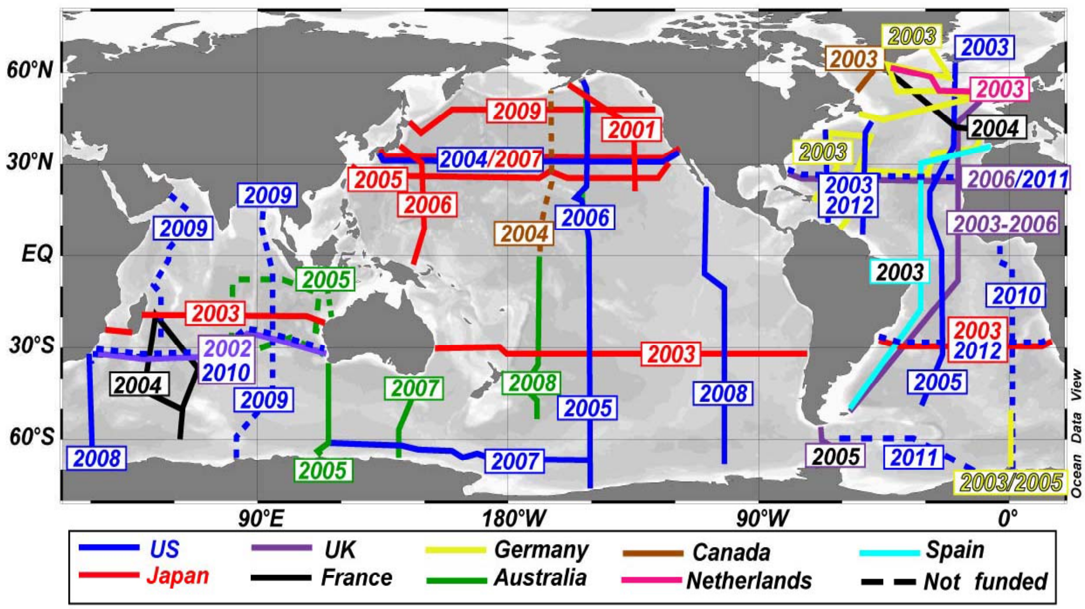


Figure 1: Proposed national and international Repeat Hydrography sections for the FY 2003-2012 period.

5.2 Volunteer-Observing-Ship (VOS) pCO_2 Surveys

The goal of the VOS program is to build an observing system of appropriate spatial and temporal resolution to constrain regional fluxes to ±0.2 Pg C yr^{-1} (Bender et al., 2002). One of the major objectives of the Carbon Cycle Science Program (CCSP) is to better characterize the spatial and temporal variability of air-sea fluxes of CO_2 in the North Pacific and North Atlantic. Currently we have a reasonably good understanding of the global scale sources and sinks of CO_2 in the oceans based on the sea-surface pCO_2 climatology developed by Takahashi et al (2002). However, there is still very little information on temporal variations of CO_2 sources and sinks. The underway CO_2 measurements will improve this constraint for the NACP and global efforts and also help place the NACP results into more of a global context by monitoring changes in air-sea

CO_2 gradients in the North Atlantic, North Pacific and adjacent coastal regions for North America that correlate with observed seasonal and interannual changes in the net North American uptake. The scientific objectives will be: a) add to the data acquired during the project to the extensive database spanning the past 40 years to improve the climatological distribution of surface water pCO_2 (Takahashi et al., 2002); b) in conjunction with the CARINA (Carbon in the Atlantic) and PICES groups provide seasonal maps of pCO_2 in the North Atlantic and North Pacific; and c) determine seasonal trends of pCO_2 across the Atlantic and Pacific and assess the effect of large-scale climate reorganizations on surface water pCO_2. Decorrelation length scale analysis (Bender et al, 2002) has shown that, on average, surface water pCO_2 measurements should be taken on 1000 km length scale and monthly time scales to constrain basinwide air-sea CO_2 fluxes to ± 0.1 Pg C yr^{-1}.

Recommendations

A US VOS pCO_2 Survey program has been funded for 2002-2008 by NOAA and includes the continuation of existing lines and the development of new lines. The seawater and atmospheric pCO_2 measurements will occur 3-4 times per hour, providing sample spacing approximately every 10 km along the trackline. The lines will be occupied approximately 6-8 times a year. Temperature and salinity will be measured continuously. A suite of auxiliary measurements (e.g., NO_3, chlorophyll, DIC-^{13}C, surface tension, O_2) will also be made though the exact composition of that suite is still under consideration. Additional funding may be required to expand the number of lines (e.g., more intensive measurement of North Pacific and North Atlantic for NACP) or for an expanded measurement suite. As currently planned and funded, the US VOS pCO_2 Survey will cover the following lines:

<u>*Atlantic Ocean*</u>

Miami to Spain This line is a critical component of the North Atlantic observations as it covers a large region of the subtropical gyre that has shown to be a large CO_2 sink through much of the year (Fig. 2).

New York to South Africa The high density XBT line between, currently on the M/V Maersk California, is a key observational line to study interhemispheric atmospheric gradients between the America and Europe/Africa (Fig. 2). The line will therefore be outfitted with atmospheric sampling equipment in the near future.

Newark to Bermuda The line on the M/V *Oleander* (Fig. 2), a container ship, operated by Bermuda Container Lines (president and CEO; Geoffrey Frith), operates between New Jersey and Bermuda each week. Repeat collection of pCO_2 data from this ship will allow us to evaluate the spatio-temporal patterns of seawater pCO_2 and the air-sea flux of CO_2 across these regions.

Iceland to Norfolk Ports of call of the M/V *Skogafoss* are Norfolk, Reykjavik, St Johns, Halifax, and Boston, with round trip duration of approximately 3 weeks (Fig. 2). The current modest sampling effort will benefit from simultaneous pCO_2 measurements as the high latitude coverage spans the northern edge of the Intermediate Mode Water formation region. The higher latitude regions experience large excursions in pCO_2 along with high wind speeds, making for large air-sea fluxes.

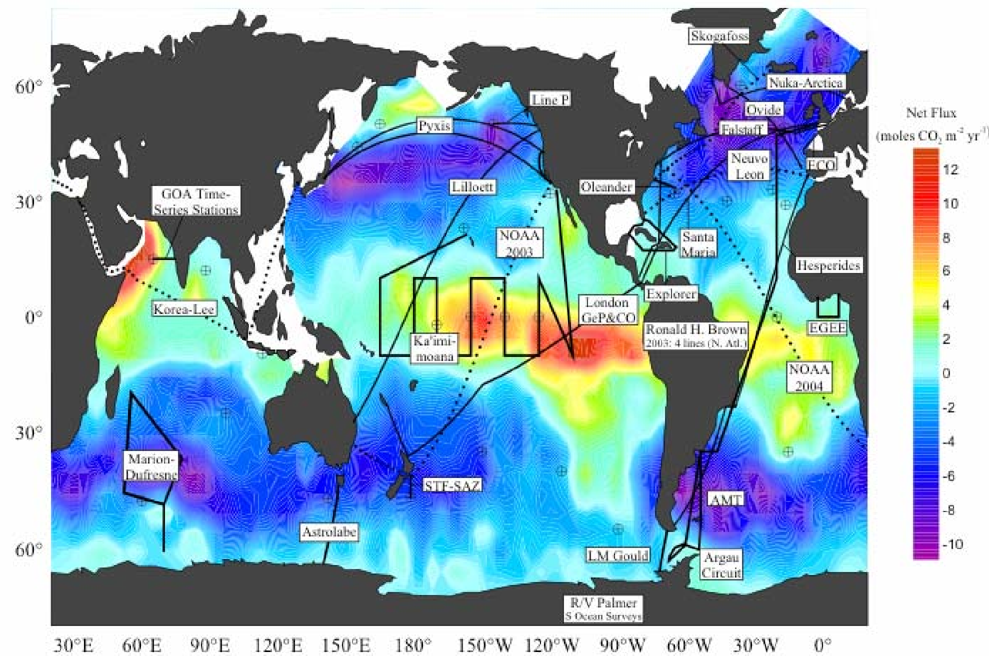


Figure 2: The pCO2 VOS lines currently maintained by US and International partnerships in the world oceans. The Atlantic partners will coordinate their efforts through the Global Carbon Project and CAVASSOO and the Pacific partners will coordinate their activities through the activities of Global Carbon Project and PICES Working Group 17. The locations of present and planned time-series stations are also shown.

Pacific Ocean

Los Angeles to New Zealand This line with ports of call: Los Angeles, Auckland, Brisbane, Melbourne, Sidney, Hawaii (Fig. 2). This line will provide both atmospheric and oceanic pCO_2 measurements along a transect from the eastern North Pacific across the equator to the western South Pacific. The line will include extensive atmospheric CO_2 and isotopic measurements by CMDL of NOAA and high precision salinity and temperature measurements by the ship observation team (SOT) of the Joint Technical commission for Oceanographic and Marine Meteorology (JCOMM). It spans more than five separate water masses along its path and complements the proposed Japanese line from Japan to South America and the east-west line onboard M/S *Skaugran*, servicing between Canada/US west coast and Japan. The NIES VOS program has recently changed VOS ships to the car carrier M/S *Pyxis* sailing between Toyohashi, Japan and Long Beach. US and Japanese scientists are presently making arrangements for international data exchanges between investigators and data management centers.

Equatorial Pacific The *Ka'imimoana* will service the TAO and CO_2 moorings in the eastern equatorial Pacific and will provide pCO2 measurements for in the tropical and subtropical North Pacific (Fig. 2).

The *Ronald H. Brown* will spend half the season in the Atlantic with focus on Western Boundary current cruises and about half in the Eastern Pacific. The cruises will therefore provide a key observational data in support of the North American Carbon Plan with focus on constraining the CO_2 fluxes from the adjacent seas.

<u>Southern Ocean</u>
RVIB Palmer The LDEO group is presently running a surface water pCO_2 program aboard the RVIB Palmer, which operates most of a year in the Southern Ocean. Once or twice a year, she sails back to a US west coast port (e. g. Port Huenimi, CA, in 2002). The data sets obtained since 1998 include repeated transects between New Zealand and Ross Sea, across the Drake Passage and into the Weddell Sea. In addition, four long meridional transects between southern Chile and Seattle, WA, and between New Zealand and Hawaii have been obtained during the transit legs.

Instrument and support are also needed for routine underway pCO_2 measurements on all of the UNOLS Class 1 research ships. The sampling coverage of the UNOLS research vessels is distinctly different in character to that of the VOS survey, providing measurements in regions outside regular shipping lanes and resupply transects and higher resolution surveys of specific regions. It also will provide an infrastructure for intensive chemical and biological process studies.

5.3 Open Ocean Time-series Measurements

Time-series records are key to characterizing the natural variability and secular trends in the ocean carbon cycle and for determining the physical and biological mechanisms controlling the system. Year-to-year variations in physics (e.g., upwelling, winter mixing, lateral advection), bulk biological production, and ecological shifts (e.g., community structure) can drive significant changes in surface pCO_2 (and thus air-sea flux) and surface nutrient fields. The biological and chemical responses to natural perturbations (e.g., ENSO, dust deposition events) are particularly important with regard to evaluating potential climate responses and for evaluating the prognostic models used in future climate projections. Time-series stations (particularly when accompanied by moorings) are also invaluable for developing and testing autonomous sensors and as focal points for process studies.

Ship-based time-series measurements are impractical for routinely measuring variability over intervals from a week to a month; they cannot be made during storms or high-sea conditions; and they are too expensive for remote locations. Instrumental advances over the past 15 years have lead to autonomous moorings capable of sampling properties of chemical, biological, and physical interest with resolution as good as a minute and a duty cycle of a year or more (e.g., Dickey, 1991; Chavez et al., 1999; Dickey and Falkowski,

2001) (Section 8.1). This work has provided a growing body of evidence that episodic phenomena are extremely important causes of variability in CO_2 and related biogeochemical properties and processes. Therefore, we emphasize supplementing existing ship-based stations with autonomous sampling technology and implementing new sites as moorings with autonomous instrumentation wherever possible. Likewise the compilation of concurrent and historical remote sensing measurements are invaluable to complement ship-, and mooring-based and autonomous measuring systems.

Recommendations

- Continued support and augmentation to include autonomous platforms and instruments for the three current American time series stations at Bermuda (BATS), Hawaii (HOT) and equatorial Pacific (EqPac). The data for these three sites will provide critical information on changes in the composition of the interior ocean waters due to circulation and ecosystem changes resulting from ENSO and extra-tropical climate variability, such as the Pacific Decadal Oscillation and the North Atlantic Oscillation.

- Addition of CO_2 system measurements to existing time-series sites in critical high-latitudes regions of the North Atlantic and North Pacific be augmented. For the North Pacific, we recommend continuation and augmentation of the Canadian JGOFS time-series at station Papa in collaboration with Canadian scientists to document the influence of the Pacific Decadal Oscillation. In particular, this study will show how the recently observed change in thermocline oxygen concentrations will evolve and how they are connected with variations in carbon storage. Because this station is regularly serviced by research ships from Canada, optimal synergisms with ship-based observations can be exploited. We also recommend support and encouragement for interaction with the Japanese time-series studies in the northwestern Pacific. In the North Atlantic, we recommend continuation and augmentation of the Labrador Sea time-series site Bravo and of the Norwegian Sea time-series site Mike, where previous studies revealed large seasonal variations (e.g., Takahashi et al., 1993). These sites are optimally placed to study the impact of the North Atlantic Oscillation on upper ocean and thermocline variability in physics, chemistry and biology.

- Extending the existing set of time-series stations into the Southern Ocean, where model simulations clearly indicate that long-term changes in response to global climate change will be most strongly manifested. Better routine observational capabilities in this sensitive area are extremely important because relatively small changes in thermohaline circulation and biogeochemistry can result in large regional changes in CO_2 fluxes and ocean storage. In addition, we recommend that time-series stations in the tropical and subtropical South Atlantic and South Pacific. We envision that several of these new time-series sites will be maintained by our international collaborators and will only require specific augmentation with autonomous sensors (Table 2).

Table 2: Proposed time-series stations as part of this program

Location	Motivation	Activity
S/BATS/BTM, Bermuda/US	NAO, Bermuda testbed mooring	Add autonomous instrumentation to ongoing time-series activity/Priority 1A
HOT Hawaii/US	PDO, ENSO, testbed mooring	Add autonomous instrumentation to ongoing time-series activity/ Priority 1A
Eq. Pacific, including 0º, 155ºW; 2ºS, 170ºW; 0º, 140ºW; 0º, 125ºW /US	ENSO variability, testbed mooring	Add autonomous instrumentation to TAO moorings/ Priority 1A
Station Papa NE Pacific/Canada	PDO	Add autonomous sampling platform/Priority 1B
Bravo Labrador Sea/Canada	NAO, subarctic response	Add autonomous sampling platform/Priority 1B
Mike Norwegian Sea/Norway	NAO, subarctic response	Add autonomous sampling platform/Priority 1B
Pacific sector of the Southern Ocean/Australia	Global warming, Antarctic Circumpolar Wave, ENSO connection	Add autonomous sampling platform/ Priority 2A
Atlantic sector of the Southern Ocean/?	Global warming, Antarctic Circumpolar Wave, THC changes	Add autonomous sampling platform/ Priority 2A
Western and eastern equatorial Pacific /US	ENSO	Add autonomous instrumentation to TAO mooring/ Priority 2B
Eastern equatorial North Atlantic (Pirata Moorings)/US	Tropical Atlantic Dipole	Add autonomous instrumentation to Pirata mooring/ Priority 2B
Western and eastern subtropical South Pacific/Australia/US	Southern Hemisphere subtropical gyre, extremely low Fe environment	Add mooring/ Priority 2B
Western and eastern subtropical South Atlantic/US	Southern Hemisphere subtropical gyre,	Add mooring/ Priority 2B

1A = 1st priority 1st 5-yr period; 1B = 2nd priority 1st 5-yr period; 2A = 2nd priority; 2nd 5-yr period; 2B = 2nd priority 2nd 5-yr period.

5.4 North American Coastal Observing Network

The continental margins of the United States, Canada and Mexico are particularly important for the CCSP and NACP. Although the area of the coastal oceans is relatively small, they are the active interface among the terrestrial, atmospheric, and marine environments. The coastal environments directly interact with terrestrial air masses and because of their sensitivity to changes in wind, river runoff and anthropogenic inputs of nutrients, are likely to be very sensitive to climate change. Carbon cycling on the continental margins is poorly understood and is under sampled to the point that it is uncertain whether these regions are a net sink or net source of CO_2 to the atmosphere. Specific objectives of new ocean margins studies are better estimates of air-sea fluxes of CO_2, exchange rates of organic and inorganic carbon between shelf waters and intermediate and deep waters of the adjacent open ocean, carbon burial rates, elucidation of factors controlling the efficiency of the solubility and biological pumps in coastal environments, quantification of the influence of margin biogeochemical processes on the chemical composition of open ocean surface waters, and the development of coupled physical-biogeochemical models for different types of continental margins. River-dominated margins and coastal upwelling regions merit special attention due to their dominant role in coastal carbon budgets.

Only a few studies have been conducted on pCO_2 distributions and CO_2 fluxes in the coastal waters of North America. The present database consists of a limited number of coastal surveys and time-series measurements at selected locations, mostly in U.S. coastal waters. While they indicate a high degree of temporal and spatial variability, some consistent patterns emerge from the limited data sets. First, regions of high biological activity lead to strong CO_2 sinks in spring and summer. The largest CO_2 sinks are apparently in the high productivity waters of the Bering Sea Shelf were nutrient inputs from Unimak Pass, coastal rivers and sediments in spring and summer are large and variable. The resulting high productivity in both the shelf and open-ocean regions of the Bering Sea causes a large and steady CO_2 drawdown (Table 3).

Table 3: Variability of CO_2 distributions and fluxes in the U.S. coastal waters from regional surveys and moored measurements

Location	Surface Seawater pCO_2 (μatm)	Instantaneous CO_2 Flux (mol/m²/yr)	Annual Average (mol/m²/yr)	Sampling Method	Reference
New Jersey Coast	211 - 658	-17 to +12	-0.65	Regional survey	Boehme et al. (1997)
Cape Hatteras, North Carolina	ND*	-1.0 to 1.2	ND	Moored measurements	DeGrandpre et al. (1997)
Middle Atlantic Bight - inner shelf	150 - 620	ND	-0.9	Regional survey	DeGrandpre et al. (2002)
Middle Atlantic Bight - middle shelf	220 - 480	ND	-1.6	Regional survey	DeGrandpre et al. (2002)
Middle Atlantic Bight - outer shelf	300 - 430	ND	-0.7	Regional survey	DeGrandpre et al. (2002)
Florida Bay, Florida	325 - 725	ND	ND	Regional survey	Millero et al. (2001)
Southern California Coastal Fronts	130 - 580	ND	ND	Regional survey	Simpson (1985)
Coastal Calif. (M-1; Monterey Bay)	245 - 550	-8 to 50	1997-98: -1.0; 1998-99: +1.1	Moored measurements	Friederich et al. (2002)
Oregon Coast	250 - 640	ND	ND	Regional survey	A. van Geen et al. (2000)
Bering Sea Shelf in spring (Apr. - June)	130 - 400	-8 to -12	-8	Regional survey	Codispoti et al. (1986)
Bering Sea (Aug. - Sep.)	192 - 400	ND	ND	Regional survey	Park et al. (1974)

*ND= no data

Note: Area of Continental Shelf between 20° and 65° including Hudson Bay = $4.06*10^6 km^2$

Note: Area of Continental Shelf between 20° and 65° excluding Hudson Bay = $3.00*10^6 km^2$

Similar conditions may exist in the coastal waters of the Gulf of Alaska, off the Columbia River in the Pacific Northwest, in the Gulf of Mexico near the Mississippi River outflow, and in the coastal regions of the Mid-Atlantic Bight (Fig. 3). Smaller river systems also lead to coastal carbon sinks, as can be seen in the near-shore regions off the Oregon coast (van Geen et al. 2001). Second, regions of strong coastal up-welling lead to strong localized CO_2 sources (Friederich et al., 2002). The associated up-welled nutrients lead to a drawdown of CO_2 due to biological productivity downstream of the upwelling zone. This coastal up-welling of CO_2 and nutrient-rich waters can be observed in the coastal areas of California, in Monterey Bay and near Cape Hateras among others. These upwelling systems are susceptible to large-scale oscillations (i.e., ENSO, PDO, NAO, etc.) in the climate system and, consequently, can turn on or shut down depending on their phase. Other regions, such as the South Atlantic Bight, are significant sources of CO_2 to the atmosphere and export inorganic carbon to the adjacent open ocean presumably supplied by the export of carbon from terrestrial sources. Accurate assessment of the net uptake of CO2 by the terrestrial system will require an accurate understanding of these coastal fluxes.

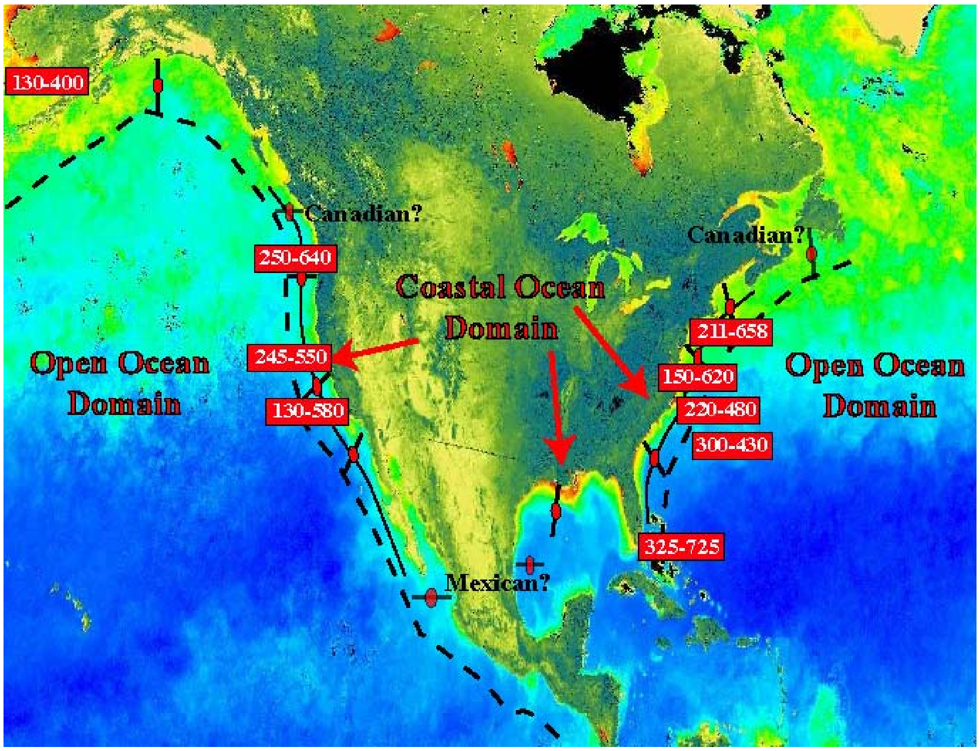


Figure 3: Range of pCO_2 values from selected coastal regions in North America. The sources for these data are given in Table 3 above. The recommended coastal time series and survey locations are also shown in the map.

It is unrealistic to use the limited amount of data on coastal CO_2 fluxes in Table 3 to obtain a meaningful annual flux of CO_2 from North American coastal waters. However, we can use a couple of different approaches to get a sense of the potential magnitude of the fluxes. Global-scale model results suggest that the uptake of carbon in coastal regions ranges from 0.6 – 0.8 Pg C yr^{-1}, and scaling by the area ratio of North American to global continental shelf (~18%) leads to an estimated uptake of 0.10 – 0.14 Pg C yr^{-1}. A second approach to constrain upper and lower bounds involves simply scaling the extremes in Table 3. Taking the area of the North American continental shelf region between 20° N and 65°N (~4 x 10^6 km^2) which includes Hudson Bay and the range of CO_2 fluxes (–8 to 1.1 mol m^{-2} yr^{-1}), the possible range is –0.4 to 0.05 Pg C yr^{-1}. At the low end, a 0.4 Pg C sink for CO_2 is potentially significant. However, the regions were long-term coastal productivity as high as is observed in the Bering Sea are probably limited to regions near large river mouths. At the high end, coastal upwelling CO_2 source regions are also probably limited by temporal and spatial constraints. The problem is we just do not have enough long-term CO_2 flux data for coastal regions to be able to constrain these estimates much further.

Recommendations

The continental margins are an area of overlap between the CCSP-Oceans and the NACP (Wofsy et al., 2003), and the proposed coastal ocean implementation plans have been developed parallel. Overall, the effort will include: (1) long-term observations using coastal transects and buoys with autonomous sensors (described here); and (2) intensive process studies of the controls on the cycling and sources and sinks of carbon and other bioactive elements (see Section 6.3). The long-term observations will be coordinated with the anticipated location of the process studies as well as with the NACP aircraft profiles and coastal terrestrial study sites to provide the most complete picture possible. Given the complexity and variability of the coastal ocean and estuarine systems, however, it is important to develop a customized sampling strategy that adequately addresses the regional conditions and leverages coastal projects that currently exist or are planned. For example, given that the footprint of the aircraft profiles and tall tower measurements is approximately 1000 km, it would be advantageous for the coastal sites to be co-located with the coastal atmospheric sampling network to help interpret the atmospheric signals obtained from these locations. Co-location of riverine studies and cross-shelf transects can provide better constraints on the ultimate fate of river borne products.

- Implement a backbone network of about dozen sampling sites (Fig. 3) along the eastern, western coasts of North America and the Gulf of Mexico, to be outfitted with surface moorings making time-series measurements needed for air-sea CO_2 fluxes, including high-quality atmospheric and ocean pCO_2 measurements. The moored platforms should also be instrumented to make marine boundary layer atmospheric measurements to compliment the aircraft profile and tall tower data.

- Conduct ship-based cross-shelf surveys past the mooring locations at monthly intervals to assess on-shore/off-shore variability and annual or seasonal survey cruises along the continental margins connecting the mooring sites to put the time-series measurements in a larger spatial context.

- Combine *in situ* observations with remote sensing to characterize regional environmental conditions at the relevant time and space scales over the margins. Satellite remote sensing data will provide routine regional estimates of key parameters. Current satellite measurements from MODIS and SeaWiFS are not yet optimized for turbid coastal waters and must be augmented with low altitude aircraft data, which can provide not only measurements for validation and algorithm development and information on carbon related parameters that cannot be derived from existing satellite systems, e.g., pulse and probe fluorometry.

- Carry out pilot coastal studies to evaluate in situ measurement accuracies, sampling strategies, and remote sensing algorithm performance need to be performed as part of the NACP intensive field activities.

Given the complexity and variability of the coastal ocean and estuarine systems, it is important to develop a sampling strategy that can adequately characterize the carbon fluxes into and out of these systems. A customized sampling strategy needs to be developed for each coastal region that leverages coastal projects that currently exist or are being planned by various agencies (e.g. NASA's coastal program) and uses a combination of in situ and remote sensing observations to characterize the unique environmental conditions of that region.

5.5 Remote Sensing

Satellite measurements will have a major role in CCSP-Oceans because of their quasi-global and synoptic temporal and spatial coverage. Satellite data are well suited for estimating the scales of variability of physical and bio-optical properties of the ocean surface (e.g., Doney et al., 2003), serving to constrain models of physical and biogeochemical processes (e.g., Moore et al. 2002). Table 4 outlines the basic set of remote sensing observables and sensors. Survey, time-series, and process cruises will offer opportunities to collect the basic observations needed for satellite algorithm development and product validation. The in situ measurement suite and sampling strategy will vary between the open ocean and coastal programs, with the spatial variability scales, and the observational platform, e.g., dedicated cruise, research ship of opportunity, VOS, mooring, float, etc. Not all satellite measurements are of adequate resolution for coastal observations, e.g., satellite salinity measurements at the 100 km scale resolution would not be useful for the coastal program.

In addition to long-standing techniques to estimate phytoplankton biomass and primary production from ocean color data, several emerging ideas warrant further testing and development, such as the methods based on remote sensing to derive gas exchange coefficients (Glover et al., 2001; Carr et al., 2002), CO_2 fluxes (Le Quéré and Gruber, 2002), and nutrient utilization (Carr et al., 1999). Related studies should determine if these effects are sufficiently large, and the relationships sufficiently robust, to serve as a basis for designing future process studies. Preliminary work along these lines has already been initiated (Le Quéré et al., 2002), but additional variables and additional relationships need to be tested.

Recommendations

- Continue algorithm development, validation, and analysis of ocean color and related remotely sensed biooptical properties. With the exception of VIIRS, all the ocean color sensors listed in Table 1 are presently in orbit. VIIRS on NPP is presently scheduled for launch in 2007 and will provide operational ocean color coverage for the NPOESS. Thereafter, VIIRS will be the primary source of ocean color data for the carbon observing system. However, VIIRS does not have the MODIS fluorescence bands and will not have a SeaWiFS-like lunar calibration capability, i.e., lunar spacecraft maneuvers such as what SeaWiFS executes monthly are unlikely for the NPOESS platforms. Much effort has been invested in the baseline ocean color products (water-leaving radiances and chlorophyll-a) and these have been validated to a large degree. While primary production and calcite are operational products, more extensive validation and algorithm refinements are needed. Other ocean color products in the table will also need substantial algorithm development and validation. These and other new capabilities (e.g., UV observations) would be requirements for a new exploratory mission.

Table 4. Ocean carbon cycle remote sensing observations.

Geophysical Quantity	Remote Sensing Platform	Status*	Coverage
Chlorophyll-a	SeaWiFS, MODIS, MERIS, GLI, POLDER, VIIRS) (Ocean color satellite sensors)	Operational[1]	Global[*]
Primary Production	Ocean color satellites	Operational	Global
Photosynthetic Efficiency	MODIS (passive fluorescence) Aircraft (lidar & passive fluorescence)	Developmental[2] Developmental	Global Local[#]
CDOM	Ocean color satellite sensors	Developmental	Global (Regional[!])
DOC	Ocean color satellite sensors	Conceptual[3]	Global (Regional)
POC	Ocean color satellite sensors	Developmental	Global (Regional)
Calcite	Ocean color satellite sensors	Operational	Global
Bicarbonate	Shipboard laser	Conceptual	Local
SST	AVHRR, MODIS, MERIS, GLI, VIIRS)	Operational	Global
Surface Wind Speed	SSMI (passive microwave) QuikScat, SeaWinds (scatterometry)	Operational	Open Ocean
Sea Level	TOPEX, JASON	Operational	Open Ocean
SSS	Aircraft (passive microwave) Aquarius (passive microwave)	Operational Developmental	Local Open Ocean

[1] Operational: currently produced by existing systems
[2]Developmental: feasibility has been demonstrated
[3]Conceptual: preliminary assessments underway
* Global: open ocean, coastal, and large estuaries (e.g., Chesapeake Bay)
# Local means limited areal sampling
! Regional: algorithm must be developed for specific biogeochemical provinces.

- Evaluate and implement remote sensing based techniques for constraining seasonal air-sea CO_2 flux variability. CO_2 fluxes are typically estimated from the air-water CO_2 partial pressure difference (ΔpCO_2), sea surface temperature SST (for solubility), and a gas transfer velocity, which is a function of surface turbulence/wind speed (Wanninkhof, 1992). Strategies have been developed to obtain global flux coverage on seasonal time scale through a combination of in situ observations, measurements from space, data assimilation and modeling. Improved high resolution winds from SeaWinds and SST and ocean color from MODIS and VIIRS should allow more accurate flux estimates. An alternative approach that is under investigation is basing the gas transfer formulation on radar backscatter rather than wind speed (Glover et al., 2001). Also, it is hoped that the Aquarius mission, if given final approval, will provide salinity data with sufficient accuracy to further improve estimates of pCO_2. Sea level data for certain areas such as the equatorial Pacific can be used to infer thermocline depth, integrated heat content, and new production.

  The development of a robust, remote sensing air-sea CO_2 flux parameterization will require a combination of coordinated mechanistic laboratory/tank and process studies (see also Section 6.4), multi-sensor/multi-platform satellite data analysis, data collection and retrospective analysis of in situ data, and dedicated field validation efforts. The determination of the pCO_2 fields, though perhaps initially derived from empirical considerations, will likely be best obtained via data-assimilation models.

6 North Atlantic and North Pacific Process Studies

While our understanding of the oceanic carbon cycle has improved dramatically in the last decade, a complete mechanistic description of the physical, chemical, and biological processes controlling the natural carbon cycle and variability has not been attained. This directly limits our ability to estimate the large-scale air-sea CO_2 flux patterns from either existing or future observation networks. The problems are more serious if one wants to predict the probable response of oceanic carbon biogeochemistry to climate change induced by rising atmospheric CO_2. A critical aspect of CCSP-Oceans, therefore, will be a series of directed process studies to better understand and quantify the biological, chemical, and physical processes that control the current and future oceanic and, ultimately, atmospheric CO_2 levels including processes that are only weakly active at present.

Most oceanographic process studies are necessarily limited to the time and space scales of one or more research cruises or expeditions. However, we know that biogeochemical processes are forced and manifested over a wide range of time and space scales. It is important to embed new process studies, where and when possible, in the context of existing or new time-series observatories (attended and/or autonomous), basin-scale surveys and remote sensing. Conversely, the results from these process studies will be also crucial for the further planning, development and optimization of the full monitoring system, in particular defining what to observe and the scales (and perhaps locations) over which to observe.

6.1 Upper Water Column Processes

The surface layer of the oceans (0-100 m) plays a key role in the development of the vertical and regional gradients of CO_2 in the marine environment due to its direct contact with the atmosphere and land margins and because the biological activity within it is largely responsible for the transformation of CO_2 into particulate matter. The biological pump serves to spatially separate organic matter production from remineralization. The more efficient the biological pump, the greater the physical separation between organic matter production and remineralization (i.e the greater the remineralization length scale). Michaels and Silver (1988) and Peinert et al. (1989) hypothesized that ecosystem structure and its associated processes play an important role in determining the efficiency of the biological pump and thus the magnitude of organic carbon exported from or recycled in the surface waters. However, the mechanisms driving its efficiency and its evolution in response to long-term environmental changes are poorly constrained.

The underlying physical / chemical make up of any given system has a direct effect on the ecosystem structure. For example, systems that experience deep convective overturn and large nutrient entrainment generally support larger phytoplankton species (diatoms, haptophytes) and grazers compared to thermally stratified systems dominated by picoplankton. As the underlying physical and chemical parameters respond to climate change it will likely have an affect on the ecosystem structure and in turn the magnitude of carbon exported from the surface ocean. At present, modeled scenarios of past, present, and future atmospheric CO_2 concentrations assume no significant alterations in the ecosystem structure that drives the oceanic biological pump, limiting the extent to which feedback mechanisms can be built into our predictive models. Hence, our restricted ability to predict ecosystem changes in the water column represents a major limitation in our capacity to model future changes in the biological pump efficiency and project future atmospheric CO_2 concentrations and global warming (Doney and Boyd, 2002).

Identified research needs

- *Biological pump efficiency:* The efficiency of the marine biological pump will be driven primarily by the imbalance in time and space between photosynthesis (organic carbon production) and respiration (organic carbon destruction). The development of a mechanistic understanding of this uncoupling may be achieved by 1) identifying the environmental factors that control the variability in plankton community structure and the magnitude of pelagic primary productivity and export, 2) understanding how these underlying environmental factors affect the community structure and in turn the partitioning of carbon into different pools, such as particulate and dissolved, organic and inorganic, and 3) characterizing the response of the heterotrophic microbial community in different regions of the water column and benthos to changes in organic matter production.

- *Controls on the stoichiometry of organic matter production and export.* Our present conceptual models assume that net plant growth is limited by nutrient availability, mostly as fixed inorganic nitrogen or iron, and that carbon cycles within an ecosystem are tightly coupled to the cycle of other bio-elements through closely constrained elemental stoichiometries. For example, carbon cycling is often derived by a mathematical scaling of the nitrogen fluxes by 6.6 (moles carbon per mole of nitrogen). Over long time-scales (annual to decadal) carbon production exported into the ocean's interior is proportional to new production. However, in this scenario the capacity of the biological pump for carbon sequestration over longer time-scales is restricted. As organic matter is remineralized it not only generates nutrients that can fuel marine primary production, but also releases CO_2. Hence, waters rich in nutrients due to the decomposition of organic matter also tend to be supersaturated with respect to CO_2 and, upon their contact with the atmosphere, become a CO_2 source rather than a sink.

Theoretically the long-term efficiency of the biological pump can be modified via several mechanisms including: 1) alteration in the availability of limiting nutrients due to changes in fluvial and aeolian transport of iron, phosphate and fixed forms of nitrogen, which may lead to a transient increase of carbon sequestration from the upper marine layer through biological activity, and 2) changes in the utilization efficiency of limiting nutrients that can effect the C:N:P stoichiometry in key food web components and alter significantly biogeochemical cycles at the ecosystem level (Elser and Urabe, 1999).

In addition the efficiency of the biological pump may also be affected by changes in the balance between its soft and hard tissue components. The biological pump removes carbon from surface waters in organic ("soft tissue pump") and inorganic ("hard tissue pump") forms. Although both pumps have for net effect the removal of carbon from the surface of the ocean, their effect in the partitioning of CO_2 between the atmosphere and the ocean is different. While the hard tissue pump decreases the ability of the upper ocean to absorb atmospheric CO_2 by increasing pCO_2 (the production of $CaCO_3$ results in one mole of $CaCO_3$ and one mole of CO_2 per 2 moles of HCO_3 assimilated), the soft tissue pump has the opposite effect. For these reasons, changes in the carbon export ratio between the hard and soft tissue pump may have major consequences in the upper ocean pCO_2 and air-sea CO_2 flux. Furthermore, only the soft tissue pump is directly coupled to the biological uptake of nitrogen, phosphorus, and iron. As stated earlier, the basic chemical and biological processes driving both biological pumps are known. However, there is still poor understanding regarding the environmental factor that may vary the ratio between both pumps.

- *Temporal variability in ecosystem structure and elemental cycles:* In order to assess the response of the marine biota to changes in climate and their effect in carbon sequestration, it is necessary to study time scales of perturbation encompassing a range of natural, as well as human induced perturbations. Changes in environmental climate may involve changes in the baseline conditions (i.e. increase sea surface temperature and water column stratification or shift in the timing of the spring transition), changes in the intensity of mesoscale perturbations (i.e. increase in storm intensity or upwelling events) or changes in the rate of perturbation events (i.e. increase frequency in hurricane, eddy activity and ENSO events). Each one of these perturbations may generate significant changes in the ecosystem structure and associated biogeochemical cycles.

- *Partitioning of exported carbon between DOC and POC.* Food web structure must be considered as a key determinant of elemental cycles, playing a major role in the transformation and partitioning of carbon among the various oceanic reservoirs. However, the fate of these carbon pools will also be affected by physical processes. For example, the removal of suspended and dissolved organic matter from the ocean surface to its interior via convective overturn has been shown to be a potentially important contributor to the biological pump in some ocean regions (Carlson et al., 1994;Ducklow et al., 1995; Hansell and Carlson, 2001). Annual global export of DOC is estimated to be 20% ± 10% of total export from the surface ocean. DOC contributes to about 30- 40% of apparent oxygen utilization (AOU) in the upper mesopelagic and < 10% in the deep ocean. However, little is known about the factors regulating the partitioning of exported carbon between DOC and POC, nor is the sensitivity of these factors to changes in environmental conditions known. Future studies must assess the factors regulating the partitioning of exported carbon between POC and DOC, its regional variability, and its sensitivity to changes in environmental conditions.

6.2 Mesopelagic Processes

Oceanic dissolved organic matter (DOM) represents one of the largest exchangeable carbon reservoirs on earth. The global dissolved organic carbon (DOC) pool is estimated to be 685 Pg C (Hansell and Carlson, 1998), a value comparable to the mass of inorganic C in the atmosphere (MacKenzie, 1981; Fasham et al., 2001). Small perturbations in the production or sink terms of the oceanic DOC pool could strongly impact the balance between oceanic and atmospheric CO_2. Thus, processes that control DOM production, consumption and distribution are biogeochemically significant with regard to carbon export (Carlson et al., 1994; Ducklow et al., 1995;Hansell and Carlson, 2001) and carbon storage in the ocean interior (Hansell and Carlson, 1998; Hansell et al., 2001).

The transfer of organic carbon from the surface ocean to the deep sea is one of the primary factors regulating the CO_2 content of the atmosphere. Roughly 90% of the organic carbon exported from the surface ocean is respired in the mesopelagic zone (approximately 100 to 1000m; Fig. 4), corresponding to the thermocline in much of the world's ocean. The thermocline is ventilated on time scales of decades, roughly an order of magnitude faster than the ventilation of the deep sea. Consequently, carbon regenerated in the deep sea remains isolated from contact with the atmosphere much longer than does carbon regenerated in the mesopelagic zone. Other things held constant, the larger the fraction of organic matter exported from the surface layer that survives transport through the mesopelagic zone to be respired in the deep sea, the lower will be the CO_2 content of the atmosphere. A complex array of physical and biological processes within the mesopelagic zone control the efficiency of organic matter regeneration, and the sensitivity of these processes to changes in environmental conditions represents a potential source of significant feedback to climate change.

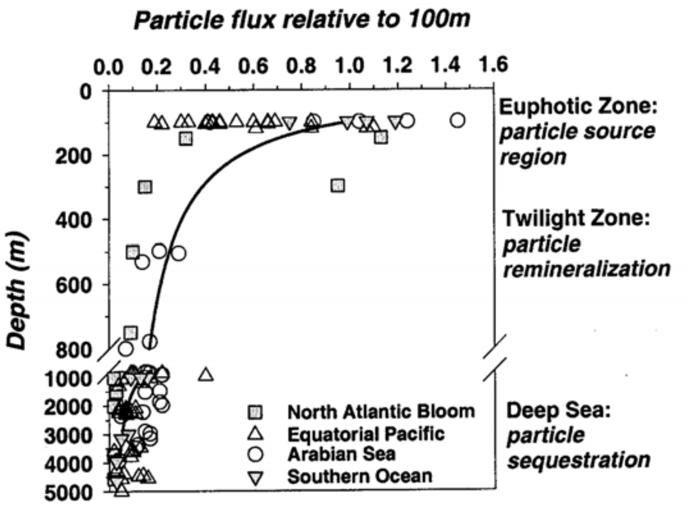


Figure 4: A compilation of all particle flux vs. depth data available from the last decade of JGOFS studies redrawn from (Berelson, 2001). Solid line is Martin curve for POC flux with b =-0.858. These data are plotted as fluxes relative to 100m to facilitate comparisons between basins.

Much was learned during the JGOFS program about the regional and seasonal variability in the export of organic matter from the surface ocean. In addition, JGOFS findings indicated that the time and depth scales of organic matter regeneration vary regionally. However, the study of the mesopelagic zone was not one of the principal foci of JGOFS, so a comprehensive understanding of the spatial variability of regeneration rates, of the factors regulating the time and depth scales of regeneration, and of the sensitivity of these factors to climate change remain undetermined. These variables represent critical parameters in models used to predict future trends in atmospheric CO_2 concentrations. Consequently, the oceanographic community has identified the factors regulating organic matter regeneration in the mesopelagic zone as a high priority for the next generation of ocean carbon research (described in many recent planning documents; e.g., OCTET, EDOCC, OCEANS, etc.).

The depth scale for remineralization of particulate organic carbon within the mesopelagic zone is regulated by the interplay between the sinking rate of particulate matter and the factors that control its conversion to a suspended or dissolved phase. Aggregation, disaggregation, dissolution, and remineralization are all factors that influence the size, composition, density and sinking rate of organic and inorganic particles. Organisms play an active role in these processes. For example, zooplankton, which are prevalent in the mesopelagic zone, can change particle size and flux as well as particle composition by physically breaking up particles via swimming and feeding or by converting POC to DOC via excretion. Coccolithophores are recorded among stomach contents of copepods because their calcareous scales resist digestion. Harris (1994), however, found that less than 50% of the calcite of coccolithophores occurred in the fecal pellets of the copepod, suggesting it had been subjected to acid digestion." Alternatively, zooplankton can increase the sinking rate of POC by repackaging suspended material into fecal pellets. Microbes reduce particle flux by converting POC to DOC via production of hydrolytic enzymes and by remineralizing organic matter that enters the mesopelagic zone

The composition of particulate organic matter changes systematically with depth. Particles in surface waters contain abundant organic compounds found in plankton, whereas with increasing depth one finds a greater abundance of compounds produced by heterotrophic decomposition, and eventually a composition dominated by a microbial signal. Uncharacterizable organic matter also forms an increasing fraction of particulate organic matter with increase in water depth. Heterotrophic organisms recycle different organic compounds at different rates; thus, the chemical composition of organic matter affects the regeneration rate and may help control the composition of community of organisms responsible for organic matter regeneration. For example microbes that colonize aggregates are genetically distinct from free-living forms. Phylogenetic diversity of free-living microbes also varies vertically, with communities in the upper mesopelagic region being considerably different than in the euphotic zone. These specialized microbial communities may take advantage of vertical gradients in nutrient and energy availability.

Changes in organic matter composition from characterizable to non-characterizable forms may, in part, be due to physical protection from biogenic and lithogenic minerals (Lee et al. 2000; Hedges et al., 2001). Ballasting by these minerals may provide a protection / packaging mechanism that allow organic / inorganic aggregates to reach the deep ocean more efficiently (Armstrong et al. 2002). Empirical observations from the US JGOFS program have demonstrated that the flux of organic matter below 1800 m is quantitatively proportional to the flux of ballast minerals. Thus better understanding of the controls on ballast mineral flux as well as POC flux are needed better predict C flux at any given depth (Armstrong et al. 2002).

Identified research needs

- *Regeneration length scales*. Empirical power-law fits to a composite of shallow floating sediment trap data (Fig. 4; e.g., Martin et al., 1987) are often used to describe remineralization length-scales and export to the deep ocean. However, the parameters used to fit these empirical relationships are found to vary from site to site, indicating that these parameters are sensitive to changes in local conditions. Predictive models must be mechanistic in nature and account for factors that influence the power-law relationship, such as climatic change, episodic bloom events, mineral ballasting, food web structure, etc. A high priority for future research is to characterize the spatial and temporal variability of these parameters, as well as their sensitivity to changes in environmental conditions.

- *Particle dynamics*. Particle size, mass and composition are all factors that determine particle sinking and degradation rates. For example, both the intrinsic lability of organic matter and the matrix in which it is packaged influence degradation rates. Both size and density can influence sinking rates; organic and mineral composition determine particle density. Future studies must examine the mechanisms by which microbial and zooplankton processes influence both particle dynamics and the regeneration of particulate organic material, as these together regulate regeneration length scales.

- *Ecosystem structure*. Recent discoveries illustrate the need for more information concerning the organisms responsible for organic matter regeneration. For example, the abundance of Archaea was established only in the past few years, and their contribution to organic matter regeneration has yet to be determined. Focused exploration may reveal additional taxa that contribute significantly to the transport, transformation and fate of organic matter in the mesopelagic zone.

- *Improved mass budgets*. Current mass budgets for organic and inorganic matter in the mesopelagic zone fail to achieve a balance between sources and sinks. For example, estimated rates of respiration by microbes and by zooplankton can each independently account for the total rate of respiration thought to occur in the mesopelagic zone. Either one or both individual respiration rates has been overestimated, or the total rate of respiration, which must equal the divergence of organic carbon flux within the mesopelagic zone, has been underestimated. Future studies must quantify better both the total rate of respiration within the mesopelagic zone, as well as the respiration rates of individual components of the food web. The sensitivity of these rates to changes in environmental conditions must be determined, as well.

- *$CaCO_3$ dissolution:* The partitioning of CO_2 into the ocean is a result of both direct sequestration and from positive feedbacks associated with the ocean's alkalinity budget. An increase in the depth of organic matter regeneration lowers the saturation state of deep waters with respect to $CaCO_3$ solubility. That, in turn, increases the dissolution of $CaCO_3$, and eventually leads to an increase in the alkalinity of the oceans in order to maintain a balance between supply of alkalinity from continental weathering and burial as $CaCO_3$. An increase in ocean alkalinity causes lower atmospheric CO_2 concentrations. The reverse of this situation applies as well. The sensitivity of $CaCO_3$ dissolution rates to changes in environmental conditions must be determined.

Strategies for the study of upper water column and mesopelagic processes

Improved technologies that are now available or are being developed that could be implemented in either or both the upper ocean and mesopelagic process study include:

- *New molecular approaches to assess changes in community structure*. New molecular tools such as polymerase chain reaction (PCR) based technologies and fluorescent in situ hybridization (FISH) probes can be used in combination with traditional biomass and rate measurements to provide qualitative and quantitative information about how prokaryotes and eukaryotes respond to various environmental factors. Understanding how the microbial community structure responds to changes in the availability and quality of inorganic and organic substrates will provide insight to how upper water column carbon is partitioned and the processes that control the efficiency of its use in the mesopelagic layer.

- *Improved moored monitoring devices*. Although continuous in-situ monitoring of meteorological and water column physical parameters has a long history, the technology to monitor chemical and biological parameter at similar temporal scales is still being developed. The availability of nutrient and gas sensors is improving rapidly as well as that of automated techniques to monitor biological diversity using molecular probes. Furthermore, optical and fluorescence techniques permit the monitoring of algal assemblages and photosynthetic activity in the upper water column.

- *Improved autonomous monitoring of carbon flux*. Bishop and colleagues have developed the "Carbon Explorer" a faster derivative of the ARGO-style float that is equipped to measure POC via optical instrumentation. These floats have recently demonstrated the ability to provide an unbroken 8-month data stream of approximately 400 POC profiles of the surface 1000 m. The Moored Profiler (Doherty et al. 1999) is an autonomous device, capable of propelling itself repeatedly along a conventional subsurface mooring line carrying oceanographic sensors through the water column. Adaptation of these systems to include optical POC measurements would provide important time-series data at selected study sites.

- *New biomarkers as indicators of transformation processes*. Organic compounds, radionuclides, and metals can all be used to indicate the bioavailability of organic matter, and how detrital material is processed by various components of the food web. Recent progress in the development of these biomarkers and in statistical approaches to their use has greatly improved our abilities in this area.

- *Improved sediment trap devices*. Hydrodynamic biases associated with surface tethered sediment traps have made accurate estimates of particle flux troublesome. Several groups (Buesseler et al, 2000; Gust et al., 2000) are working on neutrally buoyant sediment traps that reduce horizontal shear. These traps reduce the entry of "swimmers", provide a better assessment of particle quality, and estimate a higher POC flux than tethered traps (Stanely et al. submitted).

- *Naturally-occurring radionuclides*. Radioactive disequilibrium between ^{238}U and ^{234}Th has been used for more than a decade to evaluate the flux of particulate organic carbon exported from the surface ocean. New radioisotope approaches using longer-lived isotopes like ^{210}Po may extend the application of radionuclide-based flux estimates to greater depths. Multiple thorium isotopes can be used simultaneously to derive particle aggregation and disaggregation rates, as well as particle sinking rates. The principal limitation with these methods is the ability to determine the appropriate particulate carbon/nuclide ratio to use in evaluating carbon flux (Moran et al., 2003). The application of these approaches throughout the mesopelagic zone will provide more accurate estimates of particle transport efficiency through this depth horizon.

- *Improved methods to measure biological activity*. Tracers of microbial metabolic activity (adenine, thymidine, leucine, electron transport system measurements) already exist; however, rate measurements within the mesopelagic zone are sparse. Methodology used to investigate aggregated remineralization have been revised to simulate flow of water past a particle as it sinks (e.g., Ploug and Grossart, 1999). These methods would help to resolve questions about particle solubilization vs respiration rates. Another approach is to look at the products of particle decomposition (i.e., AOU). The distribution of bioactive tracers in the twilight zone constrains rates of respiration and the composition of metabolized organic matter. In addition, the development of in situ respiratory chambers would help constrain respiration on time scales more appropriate to assess specific mechanisms.

Recommendations

Technologies and approaches.

The large range of temporal scales of perturbation and response of marine pelagic ecosystems requires a multiplatform approach in their studies. In addition to ship-based sampling and observation, improved physical, chemical and biological sensors and deployment platforms, such as moorings, autonomous underwater vehicles, gliders, drifters, satellites and cabled systems, permit the continuous monitoring of key parameters reflecting changes in ecosystem structure and elemental fluxes. Deployments and maintenance of these platforms serves to develop long-term water column datasets in key oceanic regions. The resulting observations are critical in the generation of novel hypotheses linking long-term changes in carbon fluxes to environmental variability. In order to test these hypotheses, ship and laboratory-based process oriented observations and experimental manipulation are required.

The combination of a multi-disciplinary and multi-platform approach with new technological developments provides promise in resolving some of the issues listed in the previous section. Time-series programs will provide the opportunity for the refinement, integration and implementation of some of these technologies. However, it is the design and implementation of a process study or studies using these technologies, which should include mesocosms and mesoscale field perturbation experiments, that will provide an improved mechanistic understanding of the variability in the net biological production of inorganic particulate and organic carbon pools in the upper water column, and in the remineralization length scales of these pools in the mesopelagic region. The continued development of other new technologies is clearly needed. Specifically, funds should be made available for the development of better biomarkers, diagenetic indicators and sensors that measure parameters such as respiratory gasses (in-situ respiratory chamber), nutrients, transformation processes, and organism stocks. In addition it is essential that simultaneous measurements of microbial and zooplankton processes are conducted to determine how carbon is partitioned and remineralized.

In summary, we recommend: 1) the implementation and maintenance of Time-series monitoring programs in key oceanic regions (as outlined in section 5) 2) the development of process studies aimed to develop the mechanistic understanding for modeling purposes of how temporal physical and ecosystem changes in these regions affect carbon cycles, and 3) the development and implementation of novel technologies aimed to characterize ecosystem structure and quantify physical and biological transport and transformation rates of carbon pools.

Study sites.

Ideally, upper-ocean and mesopelagic process studies should be coordinated wherever possible. These process studies should be conducted in several biogeographic provinces spanning a range of environmental conditions to help identify factors that regulate production and export of organic matter in the upper water column and its subsequent regeneration in the mesopelagic zone, as well as the sensitivity of these factors to changing environmental conditions (e.g., climate change). Over the past 20 years, programs such as JGOFS, GLOBEC, CalCoFi, LTER, and LMER have provided extremely valuable insights regarding a large range of biogeochemical and ecosystem dynamics covering coastal and open ocean upwelling, oligotrophic, and high nutrient low chlorophyll (HNLC) regimes, in high and low latitude regions. New monitoring and process studies aimed to improve our understanding regarding the role of upper water column ecosystems and the mesopelagic in the oceanic carbon cycle and their response to climate change should be built upon hypotheses generated by these programs. In section 5 a map of proposed and existing time series study sites (figure 4) is presented. We recommend coordination and implementation of the upper water column and mesopelagic process studies at a subset of the proposed North Atlantic and North Pacific time series study sites (Table 2). We propose using an end-member approach, covering at least an oligotrophic gyre, an upwelling, and a high latitude site.

• *Oligotrophic Sites*

The current U.S. time-series sites at Bermuda and Hawaii offer both rich biogeochemical context and mooring and deep trap infrastructure and are recommended as initial starting points for implementation of upper ocean and mesopelagic process studies within the first five years of the program. Although these existing sites are in tropical and subtropical ocean systems there are significant ecological and biogeochemical differences observed between the North Atlantic and North Pacific subtropical gyre that have generated relevant hypotheses that could be tested through process studies; thus, we recommend that process studies in both regions be implemented.

• *High Latitude sites*

The weather stations Papa (NE Pacific) and Mike (Norwegian Sea) are examples of time series sites that provide valuable context and infrastructure in high latitudes affected by climatic changes associated with PDO and NAO respectively. We recommend that as autonomous sampling platforms are added to these stations (see section 5) at least one be chosen for the implementation of the upper water column and mesopelagic process studies in the first 5 years of the program. Furthermore, the large present uncertainty in the role of the southern ocean in the global carbon cycle requires the development of monitoring and process studies in this region (see section 7). As autonomous sampling platforms are added to the sites in the Pacific and Atlantic Sectors of the Southern Ocean (see section 5) we recommend accompanying upper water column and mesopelagic processes studies be implemented at a minimum of one site within the second 5 years of the program.

• *Upwelling sites*

Detailed discussions of the role of ocean margins in the Global Carbon Cycle can be found in section 5.4 and 6.3. Of particular interest for process studies are areas of coastal upwelling, which sustain high rates of organic matter production in the upper water column and high decomposing rates at depth. Some of these areas may be characterized by sub-oxic or anoxic regions in the mesopelagic or benthic environment supporting important biochemical processes. Over long temporal scales, these processes can alter the biochemical cycle of carbon at a basin scale. As pointed in section 6.3, process studies in these regions should be implemented in a subset of the NACP network sites.

Estimated costs

Although process studies in different oceanic regions may have different infrastructure and field sampling requirements, we envision these studies to be multi-year programs that occupy a selected site multiple times within a given year. Supporting costs will be in the range of $2-3/process study/yr with the potential for 2-3 process studies going on concurrently.

6.3 Continental Margin Biogeochemistry

Rationale

Solubility pump and biological pump processes that are focused at and unique to continental margins may account for a major portion of the total oceanic uptake of CO_2 (Tsunogai et al. 1999, Yool and Fasham, 2001). Tsunogai et al. (1999) delineated several mechanisms that may act to pump CO_2 from continental shelf regions into intermediate and deep oceanic waters (Fig. 5) and estimated that this "continental shelf pump" could be responsible for as much as a 1 Pg C sink annually on a global basis. Follow-up and global circulation modeling studies support this possibility (Wang, 2002; Vlahos et al. 2002, Yool and Fasham, 2001). Importantly, at some locations, rivers and groundwaters may supply much of the carbon transported off the shelf. This implies that assessment of air-sea exchange may not be sufficient to quantify the oceanic CO_2 sink and that terrestrial and oceanic carbon pools may be tightly linked through coastal transport processes. Additionally, nutrient upwelling and recycling near coasts support extremely high rates of primary biological production relative to the open ocean. Sea floor and water column-based estimates of the particulate organic carbon flux suggest that nearly 1/2 of the total biological pump transfer of carbon to deep waters occurs adjacent to the continents (Jahnke, 1996; Schlitzer, 2000).

Many of the lessons learned from open ocean studies cannot be applied directly to continental margin systems. Among the characteristics that differentiate margins from open ocean systems include: riverine and groundwater inputs, organic and inorganic nutrient and carbon inputs from land, altered input ratios of inorganic N, P and Si nutrients, interactions with bottom sediments, strong and direct anthropogenic impacts, high spatial and temporal variability, enhanced water column mixing due to friction with sea floor, focused and intense wind-driven upwelling, close coupling between benthic and pelagic ecosystems, elevated atmospheric inputs of dust and concentrated carbon sources associated with gas hydrates. Additionally, studies at margin sites that are likely candidates for the sequestration of carbon via direct injection are required to evaluate the applicability of this potential technology.

One conclusion of the recent RiOMAR workshop (McKee et al., 2003) is that major rivers, define “major rivers” as rivers with large inputs of dissolved and/or particulate material that is delivered directly to the ocean margin, have a disproportionately important role in biogeochemical cycles. Major river-ocean margins are potentially strong sinks for atmospheric CO_2 because of strong onshore air-flow patterns in many case and the high productivity of these regions. The large direct inputs of terrestrially-derived atmospheric C and mineral matter via runoff combine with this direct atmospheric uptake to make these systems potentially important focal points for sequestration of anthropogenic CO_2.

Identified Research Needs

To assess the contribution of margins to the total oceanic uptake of CO_2 the transport of CO_2 between the important terrestrial coastal and oceanic pools must be quantified while predictions of future carbon uptake requires detailed knowledge of individual processes and mechanisms. Given the diversity of biological, chemical and physical processes that influence carbon cycling in continental margin systems and the spectrum of space and time scales over which these processes interact, a full mechanistic understanding represents a significant research challenge. Future studies must balance the need to quantify critical carbon transfers while continuing to work toward a fundamental and mechanistic understanding of the carbon cycle.

Near margins, carbon can be exchanged amongst many important reservoirs such as coastal terrestrial biomass and soils, shelf waters and sediments, the coastal atmosphere and shallow, intermediate and deep oceanic waters. Each of these pools is characterized by different residence times and therefore a range of carbon sequestration time scales. Specific examples of important, poorly constrained fluxes, include: riverine and groundwater inputs, coastal air - sea exchange and shelf edge exchange processes such as interactions with oceanic boundary currents and eddies. In addition to transport, numerous processes within coastal systems determine the form and cycling of carbon and related biogenic elements at margins, thereby controlling transfer amongst the pools. Basic balances between coastal primary production and respiration are not well understood. The sensitivity of margin ecosystems to variations in the relative abundance of macro and micro nutrients is unknown. This is particularly important in coastal settings because benthic denitrification, sedimentary dissolution of iron and opal, and anthropogenic sources may significantly uncouple individual nutrient inputs.

Additionally, many of the sources of carbon and nutrients to the margin systems are sensitive to changing global conditions and to human activities. Examples include changing discharge rates from rivers and groundwaters and changing upwelling rates due to shifts in wind regimes and strengths. N inputs from land have increased 2-5 times since the early 1900’s (Seitzinger and Kroeze, 1998). Furthermore, a significant amount of the riverine flux of particulate and dissolved organic and inorganic carbon represent carbon removed from the atmosphere via terrestrial fixation. Understanding the fate of this carbon in margin systems is critical to evaluating net exchange with the atmosphere. Many of these exchanges will be altered through anthropogenically-driven changes to climate, terrestrial ecosystems, and the coastal environment.

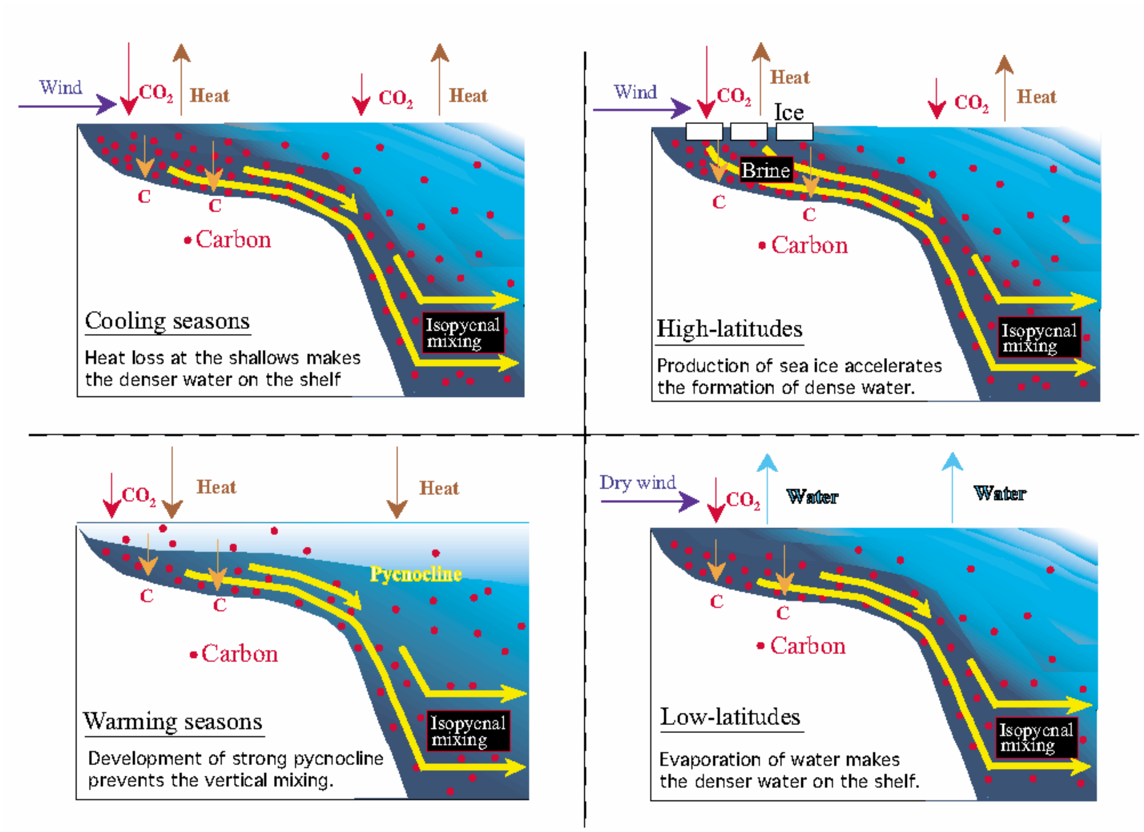


Figure 5. Schematic diagram of various mechanisms for offshore transport of carbon from continental shelf regions (after Tsunogai et al., 1999).

Recommendations

Differences in margin bathymetry, forcing processes such as wind, boundary currents, ice cover or freshwater runoff, and anthropogenic inputs result in varied and diverse pathways and magnitudes of carbon cycling and sequestration in different coastal regimes. Even preliminary estimates of carbon uptake will require studies in contrasting margin environments. Recent advances which will facilitate regional scale carbon studies, including improved models tuned to specific coastal regimes, synoptic and higher resolution coverage with remote sensing, and time-series sensor measurements. Additionally, significant advancements in the understanding of the coastal carbon budget can be made by integrative studies where processes can be clearly delineated, and longer duration studies and mapping where temporal and spatial variability can be adequately captured. One promising approach would be to perform studies in a Lagrangian frame by marking water masses. Specific recommendations for transport and process studies are provided below.

Sites: Margin types that should be examined include those characterized by high latitudes and seasonal ice dynamics, wind-driven upwelling, river-discharge and buoyancy, boundary current - shelf interactions and anthropogenic inputs. Examples of these locations would include: the Bering Sea, west coast of the US, Louisiana/Texas margin influenced by the Mississippi River discharge, South Atlantic Bight and Middle Atlantic Bight. Initial studies must focus on establishing total fluxes, eventually developing into mechanistic studies of processes such as photosynthesis, nutrient cycling, and carbon chemistry (organic and inorganic). These studies should be conducted in conjunction with the seasonal pCO_2 transects proposed in section 5.4. Because the differences in these types of margin systems are profound, each must be studied. With some overlap in the field programs, it should be possible to conduct multi-year field studies of each of these regions within a decadal program.

Transport Studies: Because margin systems have not previously been the focus of large interdisciplinary studies of carbon cycling, fundamental transports are unquantified. Initial studies need to assign a high priority to establishing the overall distribution and transport of carbon at each location. Given the high probability of significant interannual variability, detailed field observations and sampling will need to be at least 3 years in duration and should be linked to long-term observatory measurements and modeling.

Process Measurements: Intensive coastal process studies should be conducted to better understand the ecosystem and carbon cycle dynamics of each region. Integrative, process studies are needed in several areas to develop a predictive understanding of the importance of margins in the global carbon budget. Emphasis should be placed on examining processes that are expected to be sensitive to change and which may significantly alter net carbon transport. Because of the temporal variability expected, it is anticipated that continuous monitoring with in situ and remote instrumentation will be an important component of these studies. The short spatial scales associated with many coastal features will require high resolution techniques to be an important component of the remote sensing strategy. This may require the use of geostationary satellites and greater use of aircraft-based sensors. Furthermore, because many of the linkages between hydrographic, biogeochemical and ecological processes have been hypothesized but not identified and constrained, detailed process studies will remain an important strategy for margin studies. These studies should include high-resolution hydrographic measurements, such as those obtained utilizing an undulating towed instrument, extending from the near shore zone to well past the shelf break. Cross shelf and along shore transects should be conducted to examine the three dimensional complexity of dynamics and transports and repeated at an appropriate frequency to quantify major temporal variations. Many potentially important transport processes such as offshore advective filaments, particulate layers at specific density surfaces, and subducted, advective plumes may extend seaward hundreds of kilometers from the shelf/slope region. These studies must include this spatial domain.

Sea floor benthic flux (productivity, respiration, N dynamics) and deep-water tracer distributions must also be determined to assess boundary layer metabolic and nitrogen dynamics as well as deep particulate and dissolved organic carbon export. Biological measurements of metabolic rates and models of trophic controls of carbon transfers are critical to understanding present-day cycling and sequestration of carbon and for improving predictions of future conditions.

Integration of Margin Studies: Margins are the intersection of the land and ocean domains. As a reactive interface, many processes responsible for transporting and cycling carbon are accelerated within margins expanding the range of space and time scales that must be observed to provide quantitative assessments. This challenging environment, therefore, also requires multiple observational approaches, each of which may be suited for a narrower range of temporal or spatial variability. Thus, it is critical that studies of carbon cycling at margins integrate ship-board measurements and samplings, in situ and remote sensor measurements, and models. Achieving this level of integration will require coordination with other research programs.

6.4 Air-Sea gas exchange

Rationale

On seasonal to interannual timescales the ocean carbon sink can be quantified by constraining the CO_2 flux across the air-sea interface (F). Research over the last decade has shown that the this flux can be estimated through measurement of the partial pressure difference of CO_2 between water and air (ΔpCO_2) and by determining the gas transfer velocity (k), which is a function of surface turbulence/wind speed. This can be expressed in mathematical form as $F = k\ s\ \Delta pCO2$. Strategies are being developed to obtain global coverage of (ΔpCO_2), CO_2 solubility (s) (which is a known function of surface temperature and salinity), and transfer velocity on seasonal time scale through a combination of in situ observations, measurements from space, data assimilation and modeling. Significant quantitative and qualitative uncertainties exist regarding gas exchange parameterizations, hampering our ability to accurately calculate CO_2 fluxes from air-sea pCO_2 differences. Therefore, process studies need to be carried out to improve parameterizations of gas transfer velocities in terms of environmental forcing

Until recently, the gas transfer velocity was determined exclusively from indirect measurements based on mass balance techniques in the surface mixed layer. The techniques utilized natural or deliberate tracers that yielded gas transfer velocities averaged over periods of days to weeks (Lapitan *et al.*, 1999; Nightingale *et al.*, 2000). The successful improvement of direct flux techniques now makes it possible to measure the flux and determine gas transfer velocity from collocated ▪ pCO2 measurements, on the timescale of the variability of the forcing (on the order of 1 hour).

Algorithms relating gas exchange to wind speed have been developed either from compilations of field data (Nightingale *et al.*, 2000), controlled studies at a single field or laboratory site (Watson *et al.*, 1991), or a combination of field and laboratory data (Liss and Merlivat, 1986). Several recent gas exchange models are constrained by budgets of radiocarbon in the ocean (Wanninkhof, 1992; Wanninkhof and McGillis, 1999). Radiocarbon is also used as a constraint or validation of global ocean biogeochemistry models so that such parameterizations facilitate consistent observation and model-based results. Data from past field experiments are insufficient for deriving authoritative parameterizations of gas transfer velocities. Part of the problem is that measurements and forcing scales are not aligned.

Fairall *et al.* (2000) demonstrated important technical improvements that now allow direct flux measurements of CO2 over the ocean , alleviating previous shortcomings as decribed in Broecker et al. (1986). Advances in direct flux measurement techniques, and airside gradient and covariance measurements, have decreased the temporal scale to hours and spatial scale to below 1 kilometer. Successful examples include the ocean-atmosphere direct covariance method for CO_2 (McGillis *et al.*, 2001a; McGillis *et al.*, 2001b) and the gradient method for DMS (dimethylsulfide) (Dacey *et al.*, 1999; McGillis *et al.*, 2001b). The ability to measure transfer velocity locally in the field now provides the tools to properly relate the gas transfer to the appropriate forcing function. However, wind parameterizations will continue to be used extensively in the near future, both because wind is an important driver of surface turbulence controlling gas transfer, and because synoptic measurements and assimilation products of wind speed are readily available. Improvements in these parameterizations, especially in our ability to apply the relationships over appropriate time and space scales, will improve flux estimates.

Future work must be geared toward concurrent quantification of the flux with measurements characterizing the near surface turbulence that controls gas transfer. For example, capillary waves are closely related to turbulence, and transfer velocity is strongly affected by these waves (Bock *et al.*, 1999). Moreover, capillary waves generate a large radar backscatter return on altimeters and scatterometers that are in orbit to measure sea surface height and global winds on monthly and daily timescales, respectively. Another promising research avenue is to relate gas transfer to microscale breaking as manifested by perturbation of the cool skin measured by (IR) radiometer measurements (Zappa et al., 2002).

Recommendations

Most of the studies recommended should be performed synergistically with studies proposed in other programs such as SOLAS, focusing on gas transfer dynamics of other climate relevant compounds, and CLIVAR, focusing on heat and momentum exchange. The cost estimates listed below do not account for the economies of scale of joint implementation. The recommendations are presented in order of priority.

Dedicated gas exchange process studies: The two recently completed NOAA efforts, the GasEx 1998 and 2001 studies, have shown the feasibility of the direct flux measurements and have provided initial results on parameterization with forcing. Future studies should have a greater focus on parameterization using remotely sensed products, cross-validation of with independent flux techniques, and coordination with the intensive basin observations of ▪ pCO2 and time-series stations. Two areas for immediate focus are process studies of the high wind speed, bubble dominated regime and coastal waters, where surfactants, more limited fetch and other processes may lead to different gas exchange relationships than in the open ocean. A process study should included detailed measurements of the physico-chemical properties and environmental forcing (e.g., surfactants, surface wave field, near surface turbulence) as well as the implementation of direct air-sea flux measurements of CO2 and other gases, employment of proxies such as mass balance approaches of radon and deliberate tracers. The cost of these campaign type studies is $2-3 M excluding shiptime

Longer-term CO_2 flux observations: Direct flux measurements must be performed for periods of a month to several years to determine whether we can derive unique parameterizations for the gas transfer velocity, and to assess the impacts of episodic events such as storms on fluxes. Observations from fixed platforms and opportunistic research ship voyages are cost-effective. Initially, one or more easily accessible coastal observatories should be equipped, but eventually an open-ocean site should be selected to measure a range of fluxes. Possibilities include proposed the large spar buoys as part of the NSF NSF Ocean Observatory Initiative (OOI). Research ships often perform direct flux measurements of heat and momentum that require the same equipment used to determine small-scale velocity fluctuations. These cruises should be augmented to measure CO2 fluxes as well provided they fulfill the stringent measurement criteria necessary for direct CO2 flux work. Aside from measuring fluxes, accurate measurements should be taken of environmental forcing, such as friction velocity, wave slope, and surface turbulence parameters. Incorporating a remote-sensing component such as shipboard scatterometry is highly desirable. The cost for long term flux observations done in the proposed piggy-back mode is $1 -2 M/yr

Development of remote sensing algorithms: In order to optimally exploit remote sensing measurements with the objective of quantifying the air-sea flux of CO_2, we recommend the coordination of pertinent process studies, retrospective analysis, and data collection of in situ measurements. The ultimate goal is to obtain the air-sea CO_2 exchange from remote sensing platforms, which because of their nature provide the only means to obtain global quasi-synoptic fields because of the rapidly changing forcing functions. The cost is approximately $300K per study
The research effort will span a continuum from laboratory process studies to long term in situ and remote sensing observations. The process studies will be designed to improve our understanding of the factors determining air-sea exchange kinetics and the patterns and variability of oceanic pCO_2. Independent constraints should be used to determine whether regional air-sea gas fluxes are consistent with atmospheric measurements of O2/N2, 13C/12C, and 13C disequilibrium measurements between water and air.

7 Southern Ocean Pilot Studies

Rationale

Models currently suggest that processes in the Southern Ocean may play a critical role in regulating the partitioning of CO_2 between the atmosphere and the ocean. Geostrophic balance within the Antarctic Circumpolar Current (ACC) brings deep water masses to the surface where they exchange CO_2 and other gases with the atmosphere. Deep waters exposed for the first time to an atmosphere laden with anthropogenic CO_2 have a greater potential for uptake of CO_2 than do surface waters elsewhere, which are already partly equilibrated with rising levels of atmospheric CO_2. Consequently, the Southern Ocean is a region of substantial ocean uptake of CO_2, as revealed both by in situ observations (e.g., Takahashi et al. 2002) and by ocean carbon models, which indicate that about 40% of the ocean uptake of anthropogenic CO_2 occurs south of 35°S. Further, nutrients brought to the surface by wind-driven upwelling are utilized incompletely by phytoplankton in the Southern Ocean. Thus the "biological pump" is working at only about half its maximum efficiency with respect to potential CO_2 sequestration (e.g., Falkowski et al.1998).

Both the physical processes responsible for ventilation of deep water masses and the biogeochemical factors regulating the efficiency of the biological pump are sensitive to changing environmental conditions. For example, exposure of deep waters to the atmosphere is sensitive to changes in freshwater fluxes, which affects stratification and meridional overturning circulation. The efficiency of nutrient utilization in surface waters is also sensitive to changes in stratification, which influences both the light conditions within the mixed layer and the rate of nutrient supply. Nutrient utilization efficiency is sensitive, as well, to changes in chemical conditions; for example, the availability of micronutrients such as iron.

Consequently, climate-related changes in the physical and chemical environment of the Southern Ocean hold the potential to alter substantially both the physical uptake of CO_2 and its biological utilization. These effects represent some of the greatest potential perturbations of the ocean carbon cycle that may be induced by rising atmospheric CO_2 levels and global warming. Furthermore, these perturbations represent potentially significant feedbacks influencing future levels of CO_2 in the atmosphere. For these reasons, the sensitivity to climate change of the physical, chemical and biological factors regulating carbon fluxes in the Southern Ocean have been identified as a high priority for study within the US CCSP.

During the past decade, JGOFS, WOCE and related programs have generated new data from the Southern Ocean with unprecedented spatial and temporal coverage. Studies of the inorganic carbon system have revealed, for the first time: (1) the high uptake rate of anthropogenic CO_2 in the Southern Ocean, (2) the northward transport of anthropogenic CO_2 by wind-driven surface circulation, and (3) the relatively large inventories of anthropogenic CO_2 stored in regions of surface water convergence north of the ACC. Contemporary biogeochemical studies have revealed the complex interactions among physical, chemical and biological factors that regulate the efficiency of nutrient utilization and the export of organic carbon from surface waters.

Identified research needs

Our quantitative understanding of carbon fluxes in the Southern Ocean has improved tremendously thanks to these studies. However, the sensitivity of important processes that control CO_2 transfers to climate change has yet to be investigated. In order to predict future concentrations of CO_2 in the atmosphere (Goal 4 of the CCSP), it will be necessary to model accurately the factors regulating carbon fluxes in the Southern Ocean, and the sensitivity of these factors to climate change. Therefore, long-term objectives for future studies are to determine:

- The sensitivity of deep convection and meridional overturning circulation to anticipated warming and increased stratification of the Southern Ocean, as well as the impact of these changes on the rate of CO_2 uptake by the Southern Ocean's "solubility pump"; and

- The sensitivity of Southern Ocean ecosystems to the anticipated warming and increased stratification of surface waters, and the impact of these changes on the ocean's uptake of CO_2 through altered nutrient utilization efficiency and/or ecosystem structure.

While the long-range objectives above are well established, it is premature to plan at this time an intensive field program in the Southern Ocean. Results of recently-completed studies (e.g., JGOFS, WOCE) are still being synthesized, and these synthesis activities must be completed to contribute to the design of the next generation field program. Furthermore, future programs will benefit from technological developments that will permit continuous observations to be made in the remote harsh environment of the Southern Ocean, and further development of models will increase the reliability of their simulations. Therefore, during phase 1 of CCSP-Oceans, it is recommended that these synthesis activities be completed, that pilot studies be implemented and new observational systems developed, and that improvements be made to the models used to simulate the ocean carbon cycle. This effort will lay the ground work for a more intensive Southern Ocean field effort in phase 2 of CCSP-Oceans.

Recommendations

Synthesis of historical data: Many aspects of the synthesis of JGOFS and WOCE data are already well underway. For example, uptake, transport and storage of anthropogenic CO_2 are being evaluated. Rates and mechanisms of deep and intermediate water formation are being investigated, and distributions of transient tracers (e.g., chlorofluorocarbons) are being used to test the accuracy of model simulations of those processes (Dutay et al., 2002; Doney and Hecht, 2002). Other tracers (e.g., ^{14}C, ^{3}He, Si) are being used to constrain the rates and pathways of deep water transport and ventilation in the Southern Ocean. Results of individual biogeochemical process studies are being combined to produce vertical carbon budgets throughout the water column, as well as new insights into the flow of carbon and nutrients through the marine food web. Work in these areas should continue.

New synthesis efforts should be initiated to investigate interannual variability of carbon fluxes in the Southern Ocean and of the factors regulating these fluxes. Regular patterns of interannual variability associated with coupled modes of ocean and atmospheric circulation have been identified in the Southern Ocean. The Antarctic Circumpolar Wave (ACW) propagates around the Southern Ocean with a period of about eight years and a wave number of two. Sea ice extent (SIE), sea surface temperature (SST), sea surface height (SSH), sea level pressure (SLP), and wind stress all vary systematically with the phase of the ACW (White and Peterson, 1996). The Antarctic Dipole (ADP) is a quasi-stationary wave that is characterized by an out-of-phase relationship between sea ice and temperature anomalies in the Atlantic and Pacific sectors of the Southern Ocean (Yuan and Martinson, 2001). Both the ACW and the ADP have strong statistical relationships to ENSO. The Southern Hemisphere Annular Mode (SAM) is characterized by an out-of-phase relationship between surface air pressure at the pole and the pressure at mid latitudes (Thompson and Wallace, 2000) The intensity of the Southern Hemisphere westerlies depends on this pressure gradient and, in turn, influences surface ocean circulation, sea ice extent, and meridional heat transport (Hall and Visbeck, 2002).

Future field programs may exploit the quasi-regular variability of these natural oscillations to investigate the sensitivity to changes in environmental conditions of the factors regulating carbon fluxes in the Southern Ocean. To assess the feasibility of such an experimental strategy, remote sensing data should be analyzed to determine if correlations exist between the phase of these oscillations and derivable parameters relevant to ocean carbon fluxes.

Completing the synthesis of historical data will also provide a context in which to interpret the results of process studies conducted by various national JGOFS programs. Individual process studies were of a duration of no more than one year, and some were much shorter. Consequently, the extent to which the results of these studies represent climatological mean conditions is unknown. The analysis of historical data will place each process study into a larger context of the mean and variability of the local conditions that influence carbon fluxes, such as wind stress, sea surface temperature, sea ice extent, etc.

Pilot Studies and Technological Developments: Technology development in support of future ocean carbon studies is described in Section 8.1, and the instrumentation of Volunteer Observing Ships (VOS) for pCO_2 surveys is covered in Section 5.2. All of these activities are of importance in preparation for future studies in the Southern Ocean, where the remote location and harsh operating conditions make it both difficult and expensive to conduct shipboard operations. Remote sensing, both from space and from in situ observational networks, will necessarily play a large role in future Southern Ocean studies. During the next five years, a few activities can be noted as being of high priority.

Autonomous pCO_2 systems have been installed aboard the RVIB Nathaniel B. Palmer and the ARSV Laurence M. Gould, the two principal U.S. ships supporting oceanographic research around Antarctica. This program must be maintained, and it should expanded, as well. For example, pCO_2 systems could be installed aboard Coast Guard ice breakers, aboard ships supplying research bases (both U.S. and foreign), and aboard cruise ships that frequent certain regions of Antarctica. With further development of pCO_2 sensors, sensor-bearing drifters can be deployed from ships transiting the Southern Ocean, thereby increasing the capacity for in situ observations. Developing a large data base of repeated pCO_2 surveys on VOS, supplemented by sensor data from drifters, will provide essential information with which to evaluate the interannual variability of air-sea CO_2 fluxes in the Southern Ocean. Integrating the CO_2 data with remote sensing of environmental parameters (SST, SLP, SSH, SIE, winds, etc.) that characterize the modes of variability described above (ACW, ADP, SAM) will lead to a first assessment of the response of air-sea CO_2 fluxes to surface forcing associated with these modes of variability. Assessing the interannual variability of CO_2 fluxes, and any relationships between this variability and regular patterns of surface forcing, will provide an informed basis for designing future field programs in the Southern Ocean.

Model simulations of CO_2–induced global warming predict increased stratification and reduced overturning circulation in the Southern Ocean caused by an enhancement of the hydrological cycle. Model simulations also predict that one of the first detectable consequences of increased stratification would be a reduction of the concentration of dissolved oxygen at intermediate depths (roughly 350 to 1000m). An analysis of historical data suggests that these predicted changes are already underway (Matear et al., 2000). However, the historical data with which to detect climate-related changes in ventilation of the Southern Ocean are limited. A high priority for future research in the Southern Ocean is an early warning system that would detect predicted changes associated with global warming, such as decreasing concentrations of dissolved oxygen at intermediate depths. Ideally, this system would involve moored oxygen sensors deployed at strategic locations around the Southern Ocean. However, oxygen sensors presently lack the stability required for long-term deployments (Section 8.2). Designing an early warning system to detect climate-related changes in circulation and ventilation of the Southern Ocean is a powerful incentive to develop oxygen sensors capable of long-term stability. Until sensor-based monitoring of oxygen concentrations becomes feasible, ships of opportunity should be exploited to expand the measurements of oxygen concentrations in intermediate waters.

Model Development: The comparison of ocean carbon cycle models by OCMIP revealed some important features about the Southern Ocean, as well as some issues in need of attention. Ocean carbon models generally show the greatest uptake of anthropogenic CO_2 south of 50°S, in part due to the exposure to the atmosphere of old deep waters that have never before been exposed to anthropogenic CO_2. For this reason, models also show the Southern Ocean becoming increasingly important as a sink for anthropogenic CO_2 during the next century. Whereas there is agreement among ocean models that the Southern Ocean is a site of substantial uptake of anthropogenic CO_2, the Southern Ocean is also the region in which the greatest disagreement exists among models in terms of absolute uptake rates, with results varying by as much as a factor of three among models. The source of these inconsistencies must be determined.

Large discrepancies exist between the ocean's uptake of CO_2 at high southern latitudes inferred from ocean observations and those obtained from atmospheric models. Interpretation of atmospheric data point toward a smaller Southern Ocean sink than would be estimated from ocean observations or from ocean models. The source of these inconsistencies must be determined.

8 Synthesis and Numerical Modeling

Rationale

Despite near-term advances in in-situ measurements and remote sensing, ocean and atmosphere carbon observations alone will remain too sparse to fully characterize the relevant time-space variability of the marine carbon cycle and the net air-sea carbon fluxes with the atmosphere. Numerical modeling, including data assimilation, therefore, will play a pivotal role in the synthesis and interpretation of carbon cycle data. Modeling considerations also should be incorporated from the beginning in the development of a global observational strategy and process studies, with particular focus on sampling network design, timely public access to data, and field data to address known model deficiencies. The overall CCSP focus on "what will be the future atmospheric CO_2 concentration," can only be answered with prognostic models, the improvement of which must therefore be a central goal of ocean carbon cycle research over the next decade.

More specifically, numerical models that incorporate the relevant carbon cycle processes are necessary for the following tasks: designing optimal observing strategies especially in the context of a changing climate and circulation; inferring regional carbon sources/sinks consistent with atmospheric CO_2 variations using diagnostic "inversion" techniques; synthesizing diverse ocean/atmosphere/land observations into a coherent internally-consistent framework; scaling-up knowledge gained from local process studies; testing mechanistic hypotheses about the varying sources and sinks of CO2; "hindcasting" historical variability on seasonal to decadal time-scales as a measure for evaluating model skill; providing high resolution physical circulation and biogeochemical context for regional campaign and process style experiments; and projecting future responses and feedbacks to climate change on centennial timescales.

Research Strategy

Three activities are envisioned here as a direct part of CCSP-Oceans:

- Prognostic (forward) oceanic circulation/biogeochemistry models,
- Diagnostic (inverse and data assimilation) versions for the same ocean models,
- Reconciliation of ocean/atmosphere air-sea CO_2 flux estimates

The carbon cycle is embedded in the physical climate system, and close collaboration with the weather, physical oceanographic and climate observational and modeling communities is imperative, and will be synergistic and mutually beneficial.

Prognostic Modeling: Focused research on improving forward or prognostic models is also required in order to improve future climate projections and to develop a better fundamental understanding of the ocean carbon cycle at a mechanistic level (Doney, 1999). This work can often occur hand in hand with diagnostic modeling. The IGBP-GAIM Ocean Carbon Model Intercomparison Project (OCMIP) has laid out a basic framework for comparing global-scale ocean carbon models against observations in terms of their physical circulation (simulated hydrography and transient tracer distributions) and basic carbon system parameters. An expansion of this effort to ecosystem components is needed. This will require the development of standard experiments and evaluation of data sets as well as close collaboration among ocean modeling, field and remote sensing communities. In addition to replicating the large-scale geographic patterns of the mean state and seasonal cycle, particular emphasis should be placed on evaluating the ability of prognostic models to hindcast the ocean carbon cycle and biogeochemical responses to interannual to decadal natural variability (e.g., climate modes like ENSO, NAO; the North Pacific regime shift, etc.).

Diagnostic Modeling: Diagnostic modeling (inverse models up to full data assimilation systems) provides a means to generate complete, dynamically consistent ocean carbon fields that incorporate data when and where they are available, and that give rigorous estimates of uncertainties on the inferred quantities. These model-generated products provide the input needed for scientific and political assessments of the state of the ocean and its role in the global carbon cycle. These products can also provide initial conditions for short-term and long-term predictions using prognostic models. Inverse models also offer a formal method for designing optimal observational networks, evaluating the quality of observational data, assessing the adequacy of model parameterizations and parameter sets, and investigating the overall quality of model structure. Diagnostic modeling therefore provides a natural framework for integrating the different elements of ocean carbon cycle research: *in situ* observations, satellite remote sensing, process studies and prognostic modeling.

The two main components of the proposed diagnostic modeling framework are ocean carbon data centers and ocean carbon data assimilation systems. The ocean carbon data centers act as the collection points for the various types and levels of data streams. For many types of data, particularly for those collected on space-borne platforms, such centers are already in existence. However, for many other data streams, for example, those associated with the rapidly increasing number of underway pCO_2 data, such data centers need to be established and supported. The data synthesis efforts at these data centers should also include quality control procedures that extend beyond the initial quality control done at the level of the individual observations. This includes, for example, investigation of the internal consistency of the data as well as testing for long-term precision and accuracy of the data. High priority should also be given to fully documenting the various data products and streams (metadata). Diagnostic mathematical methods have only very recently begun to be used in global carbon cycle research. These models can range in their spatial coverage from regional to global and can be of various complexities in both their mathematical approach as well as in their biogeochemical representation.

The main products will be an optimal estimation of the current sources and sinks of CO_2 in the ocean and of the state of the ocean carbon cycle in general (e.g., primary productivity). Three main groups of users can be identified: the oceanographic, atmospheric and terrestrial research community; the scientific assessment and policy communities; and commercial fisheries and fishery managers. However, at present, availability of existing expertise and experience to judge which method to apply to a particular biogeochemical problem is scarce. It is therefore imperative that resources be allocated to develop and test different schemes on a variety of temporal and spatial scales, making use of a large variety of data.

The exact nature and structure of an ocean carbon diagnostic modeling framework is an open question that requires fundamental research. Data assimilation in physical oceanography, while not as advanced as in the weather forecasting community, has made significant progress over the last several years. Several programs have been initiated at the international level such as GODAE (Global Ocean Data Assimilation Experiment; http://www.bom.gov.au/bmrc/mrlr/nrs/oopc/godae/homepage.html) and at national levels, e.g. ECCO (Estimating the Circulation and Climate of the Ocean; http://www.ecco.ucsd.edu) within the United States or MERCATOR in France. The fundamental objective of GODAE is a practical demonstration of real-time global ocean data assimilation in order to provide a regular complete depiction of the ocean state at time scales of a few days, space scales of several tens of kilometers, and consistent with a suite of remote and direct measurements and appropriate dynamical and physical constraints. One of the associated objectives includes a description of the ocean circulation and physics upon which ocean carbon models can be developed and tested. Interactions and synergies with these ongoing and future activities must therefore be established as soon as possible and supported into the future.

Ocean-Atmosphere Reconciliation: Uncertainties associated with determining regional- to basin-scale oceanic CO_2 fluxes are such that comparing different approaches is critical. These include interior and surface ocean measurements, atmospheric measurements, and global mass-balance. Oceanic and "top-down" atmospheric carbon cycle estimates have been compared in the past with generally consistent agreement on global to hemispheric, and decadal, scales [e.g. Houghton et al., 1995; Prentice et al., 2001]. However, comparisons on basin/continental and interannual scales show considerable disagreement [e.g. Gurney et al., 2002; Le Quere et al., 2000]. Direct integrations have primarily consisted of applying oceanic flux estimates and their uncertainties as prior constraints in synthesis inversions of atmospheric data [e.g. Gurney et al., 2002; Fan et al., 1998]. Because of data and model limitations, the basin-scale ocean fluxes, the within-basin flux patterns, or both are fixed by prior assumptions and not allowed to change, leading to potentially large biases in the calculated fluxes.

In many cases, the *a priori* ocean fluxes are set by the Takahashi et al. [1997] 30-year climatology of surface pCO_2 measurements and the Wanninkhof et al. [1992] parameterization of air-sea gas exchange. Of particular relevance to top-down flux calculations are how uncertainties in applying such estimates to represent the basin-scale fluxes or their patterns in any particular month propagate through an inversion. In planning for a focused study such as the North American Carbon Program [Wofsy et al., 2002], it is important to consider specifically how uncertainties in oceanic values will affect the top-down terrestrial estimates. For example, given a north-south distribution of atmospheric CO_2 the currently large uncertainties in the wind-speed dependence of gas-exchange could translate directly into uncertainties in the latitudinal distribution of sources on land. Presently, because the uncertainties associated with undersampling and model biases over continents are relatively large compared to the constraints placed by marine boundary layer atmospheric CO_2 measurements, reducing the *a priori* uncertainties on ocean fluxes does not significantly improve inverse calculations (Law et al., 2002; Gurney et al., 2002; Bender et al., 2002). Nonetheless, as atmospheric observations expand, particularly over the continents, the uncertainties on ocean flux estimates will become more important to inverse calculations. Future calculations will require air-sea flux estimates from concurrent measurements rather than a climatology, and a data-assimilation technique rather than a synthesis inversion.

Furthermore, even if the total flux for an ocean basin is known, large errors can be introduced to atmospheric inversions if the spatial patterns of those fluxes are uncertain [Kaminski et al., 2001; Engelen et al., 2002; Gloor et al., 1999]. These "aggregation errors" are predicted to have large effects on flux estimates for the local region, and to also affect neighboring regions. Engelen et al. [2002] estimated that reasonable uncertainty in terrestrial carbon flux patterns would lead to 20-30% uncertainties in North Pacific and North Atlantic fluxes. Also, basin-scale fluxes and within-basin flux patterns vary interannually. The largest interannual variations in ocean CO_2 fluxes appear to be associated with El Niño events, with on the order of 0.7 $PgCyr^{-1}$ less CO_2 entering the atmosphere from the eastern equatorial Pacific [Feely et al., 1999b; Chavez et al., 1999, Le Quéré et al., 2000]. Other significant sources of interannual ocean carbon cycle variability include the North Atlantic Oscillation (NAO) and Antarctic Circumpolar Waves [Le Quéré et al., 2000; Russell et al., submitted to GBC 2003]. Errors in these variations, or assuming fluxes or patterns fixed in time, can lead to biases in the attribution of interannual carbon cycle variability using top-down approaches. For example, with insufficient ocean observations the distinct regional responses to NAO within the North Atlantic identified by LeQuéré et al. [2000] could look to the atmosphere like variations in terrestrial fluxes from North America and Eurasia.

All independent approaches to constraining the global carbon cycle have unique advantages and limitations, and the best estimates will likely ultimately come from a synthesis of all available measurements in a data-assimilation scheme. Yet, atmospheric, terrestrial, and oceanic observations, and carbon modeling and data-assimilation approaches are still in a state of evolution. Without knowing the details of these developments, we can anticipate a continued important role for direct comparisons between oceanic and top-down estimates. Targets for uncertainties on top-down atmospheric constraints are on the order of +/- 0.2 $PgCyr^{-1}$ for individual months and regions, with additional information on the subregional spatial distribution of these fluxes [Sarmiento and Wofsy, 1999; Wofsy and Harriss, 2002; Bender et al., 2002]. It is important that our ocean observations evolve in parallel with atmospheric and terrestrial observations so that independent estimates of these fluxes can be made at the same resolution, and erroneous results and/or models be identified.

Recommendations

The synthesis and modeling component should include the following components:

- Augmented/new carbon data centers to undertake or coordinate the compilation, quality control and distribution of in-situ and remote sensing data relevant to the ocean carbon cycle, as well as derived synthesis products (e.g., surface fluxes; assimilation fields);

- Process and inverse modeling studies to design optimal sampling networks and assess the utility and trade-offs among existing and emerging measurement and platform technologies;

- Ongoing development, improvement, and data-based evaluation of ocean circulation/biogeochemical models used to diagnose carbon sources and sinks and attribute observed changes in ocean carbon storage to variations in circulation, biology, and chemistry.

- Comparison and reconciliation of independent estimates of global and regional air-sea CO_2 fluxes from direct observations, atmospheric inversions, and oceanic forward model solutions and inversions.

- Hindcast simulations (prognostic) and data synthesis of the ocean carbon cycle variability over the recent historical period (1950s--present) using atmospheric reanalysis products and ocean state estimations;

- Pilot data assimilation studies to investigate the methods, data needs, and general feasibility of ocean carbon data assimilation systems. In the longer term, the synthesis and modeling component must migrate to full data assimilation systems in order to provide ongoing evaluations of carbon sources and sinks and the underlying mechanisms.

- Prognostic ocean carbon and coupled climate-carbon model development and simulations to improve and refine projections of the future evolution of the carbon cycle under various scenarios for emissions, land-use etc.

- Model tools to support national and international carbon cycle and climate assessments and to characterize the efficacy and environmental impacts of ocean carbon management/mitigation strategies.

Relationship to other program elements: Numerical modeling is synergistic in one manner or another with all of the other implementation elements. For example, data assimilation will produce a representation of the past and present state of the ocean carbon cycle that is optimally consistent with all available data-hydrography, pCO2 surveys, time-series, remote sensing, and floats/drifter-maximizing the utility of these datasets. Models will allow observing system simulation exercises to guide the optimal implementation of the observing system and will incorporate the results of these process studies, thereby extrapolating their impacts and feedbacks to regional to global, and decadal to centennial scales. Process studies will also be targeted to provide data to address major model uncertainties, which will be critical for discriminating among and improving models. The success of ocean carbon data assimilation for various types of measurements (in situ and remote, real and pseudo) will provide important guidance for technology development of new sensors and platforms. The modeling work will make use of the synthesized data products from the data center(s) and will return model products to be distributed. In the past, synthesis and modeling work has been conducted in a highly international collaborative framework (e.g. Gurney et al., 2002) and this work will encourage similar linkages by making the data freely available to international collaborators for their modeling work. A number of workshops should be conducted to advance the modeling and synthesis program elements. The products of the modeling and synthesis will be very useful to policy makers and educators.

9 Enabling Activities

9.1 Sensor and Platform Development

This section addresses technological developments that will enhance our ability to study the surface and subsurface structure of all interacting carbon components on key time and space scales. Some of these developments are operational, others are in development, and others are anticipated through continued research. This section focuses on autonomous in-situ ocean carbon cycle measurements; but to quantify, understand, model, and predict CO_2 variability of the atmosphere-ocean system will also require complementary measurements of meteorological and surface ocean variables. These needs are met not only by field programs, but also by excellent real-time satellite and weather prediction model products such as wind, irradiance, aerosols, and biomass assessments. Autonomous instrumented platforms are necessary given that many of the oceans biologically dynamic realms are under-observed because they lie in areas of almost perpetual cloud cover (Bishop and Rossow, 1991) or beyond the reach of satellite remote sensing.

Platforms

High powered systems: deep-sea and coastal moorings, cabled observatories, and AUV's: Moorings are the most mature technology available to support autonomous CO_2 measurements and have proven invaluable in testing and development of new complex sensors and seawater sampling systems. Fixed and profiling sensor/sampling packages are now capable of season-long deployment from deep-sea moorings or from the bottom platforms on continental shelves. Opportunities are emerging for adapting biogeochemical instrumentation developed for moorings into deep-sea and continental shelf cabled observatories, which offer the potential for high speed, real-time two communication capabilities (Glen and Dickey, 2002). Self-propelled high-powered Autonomous Underwater Vehicles (AUV's) capable of navigation over 1000 km distances and several week durations are now being proven at sea. AUV technology would be best applied in high-resolution studies of smaller ocean areas, such as in coastal observatories like LEO-15, rather than in sustained monitoring activities. The strength of high-powered systems is their ability to sustain complex sensor and sampling systems. The high cost of such systems, however, dictates a limited and careful deployment in the world oceans (Section 5.3).

Low powered systems: drifters, profiling floats, gliders. The attraction of the low power systems is their low deployment cost (about one to two days of ship operating costs), simplicity and ruggedness, which permits wide-scale deployment on global scales.

In both profiling floats and gliders, accuracy of sensor data can be verified by sampling deep water.

Drifters: Drifters were developed to track ocean currents and ocean temperature in support of the WOCE program. Drifters typically last about three months, and because they provide a unique Lagrangian perspective on biogeochemical processes, they can clearly enhance shiptime science during process studies by tracking features of interest. Data are relayed in real time via ARGOS satellite system. However, drifters provide no information on the ocean interior and only limited meterological information. Platforms with a larger instrument suite required for chemical monitoring have not been extensively tested, and their long-term survivability in the surface ocean is an open question, although the CARIOCA buoys (CARbon Interface OCean Atmosphere) (Hood et al., 1999; Bakker et al., 2001; Hood et al., 2001a,b) have proven succesful, and WOCE- style drifters enhanced with passive radiance and irradiance sensors have been successfully deployed by the Oregon State University remote sensing optics team.

Profiling Lagrangian floats: Thousands of floats are now being deployed globally as part of the international program *Argo* (*Argo* Science Team, 1998; Roemmich et al., 1999), which aims to provide widespread temperature and salinity profiles and information on mid-depth circulation for investigation of the climate of the ocean. These buoyancy driven systems are pre-programmed to profile to the surface from kilometer depths once every ten days over five years; at each surfacing data is transmitted to the ARGOS satellite system. The fast telemetry speeds via ORBCOMM reduce the time required for data transmission; e.g. for *Argo* floats, from days to tens of minutes. This not only saves energy (which can be used to power additional sensors), but also reduces euphotic zone time and the need for anti-biofouling requirements. Coverage of ORBCOMM satellites falls off strongly poleward of 55°N and 55°S; development of a ‘smarter’ success-driven communications protocol will enhance data throughput at higher latitudes. IRRIDIUM data transmission methodology, which is currently under development and testing, will not suffer from lack of coverage in polar regions.

The advent of fast (20-50 times faster) bidirectional data telemetry via the ORBCOMM and IRRIDUM satellites has enabled a significant expansion of the sensor suite that can be carried on an *Argo*-style profiler, including carbon sensors. Six of these outfitted profilers ("Carbon Explorers"; two in at Station PAPA in the North Pacific, and four in the Southern Ocean) have been deployed and operated successfully over the past two years, and have proven to be capable of sustained, high-frequency observations of carbon biomass variability in the ocean for the greater part of one year. These greatly increase the probability of directly observing biological responses to episodic events such as storms and dust inputs (Bishop et al., 2002). The 10 day *Argo* profiling frequency is a poor match for upper water column carbon cycle processes. However, instruments capable of determining the variability of carbon sedimentation would be perfectly compatible with the *Argo* floats as they are now operated. Future designs need to consider matching platform capabilities, sensor stability, with timescales that are useful for carbon cycle research. The Station PAPA floats, for example, combined a variety of profiling depths and frequencies that captured the diurnal cycle in the upper water column as well as the longer-term variability of waters to kilometer depths.

Gliders: Gliders are steerable profiling floats capable of self navigation at speeds of 0.2 m sec^{-1}. "Slocum" (WEB Research); "Spray" (named after Slocum's boat; SIO); and "Seaglider" (APL) are examples of gliders that are now being proven in both coastal and open ocean environments. Gliders are capable of sustained operations to depths as great as 2000 m and for time periods of seasons. Operation farther than 20 km from shore requires bidirectional ORBCOMM or IRRIDIUM satellite telemetry. Gliders are more expensive than floats ($35-50k versus $15-20k), but they are also more easily recovered since they can be commanded to navigate to a recovery point. Mechanical integration of sensors on gliders is more problematic than on profiling floats because sensors must not compromise hydrodynamic performance.

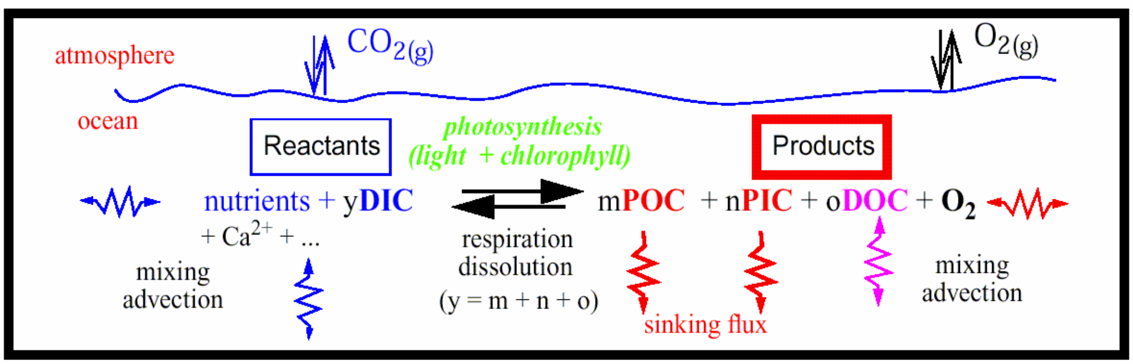


Figure 6.2.1 *A simplified representation of the transformations of the carbon system components in seawater. In the presence of light, marine plants fix nutrients and dissolved inorganic carbon (DIC) species into particulate organic carbon (POC, biomass), particulate inorganic carbon (PIC, as calcium carbonate shells, or liths), and dissolved organic carbon (DOC) pools. The DIC pool (or* ΣCO_2*), is comprised of aqueous* CO_2 *,* H_2CO_3 *,* HCO_3^- *,* CO_3^{-2} *components. In surface waters, DIC dominates all forms of carbon in seawater and is present at concentrations of ~2000 µM. Next in importance is the DOC pool at ~70-100 µM. The POC and PIC (*$CaCO_3$ *: as calcite and aragonite minerals) pools rarely add up to more 10 and 2 µM, respectively. PIC is important because it is forms the 'ballasting'of marine aggregates and thus influences the vertical transport efficiency of sedimented POC. In surface waters, the dynamic range of these parameters is in opposite order: 10% (DIC), ~30% (DOC), and factors of 10 to 100 for both POC and PIC. This is why diurnal variability in particulate matter concentrations is easily detected even in oligotrophic waters, whereas diurnal variability of DIC or DOC are smaller than measurement error.*

Carbon, oxygen and nutrient sensors

Progress on sensor development was recently reviewed by Johnson et al. (2000). Below we highlight sensors with near term prospects for deployment across all autonomous platforms. We recommend agressive investment to bring an integrated suite of carbon system sensors to operational status over then next several years. Issues that must be addressed in the near term include long term sensor accuracy and stability: e.g. limitations by biofouling, and in some cases, supply of reagents.

pCO_2: Autonomous shipboard pCO_2 systems have been successfully reengineered and deployed on surface drifters and moorings. A time series of ΔpCO_2 measurements on TAO/TRITON moorings in the equatorial Pacific (Chavez et al., 1999) now extends over two years, which indicates the growing maturity of the technology. These autonomous pCO_2 systems, which are based on infrared analyzers, work well in the surface ocean, but are not easily adaptable to depth profiling. On the other hand, systems such as Differential Gas Tension (DGT) devices with CO_2 specific chemical absorbers show great promise for in-situ pCO_2 measurement (e.g. DeGrandpre, U. Montana; L. Merlivat, LODYC), as they are low power and have no inherent depth limitation. Adaptation of this system for deployment on low payload platforms will require a reduction in size and in the time constant for measurement from minutes to tens of seconds.

DIC: The components of dissolved inorganic carbon can be determined by measurement of two independent carbon dioxide parameters (DIC, TA, pH, pCO_2). Currently, these can only be determined with required precision and accuracy using shipboard and laboratory methodology (see section 5.1). Seawater pH has been measured using spectrophotometric procedures similar to those used for pCO_2 sensors, and methods for autonomous determination of total dissolved inorganic carbon (C_T) and total alkalinity (TA) have been proposed and are in initial stages of development. However, all DIC component sensor strategies need engineering investment to decrease time constant from minutes to seconds in order to meet profiling applications.

DOC: Measurements of dissolved organic carbon must be made from ships. There is an excellent opportunity to exploit recent advances in microelectronics / biotechnology to develop robust and stable sensors capable of autonomous assessment of DOC in the sea. Directed investment would yield an operational sensor within several years.

POC: Beam attenuation coefficient (measured using a transmissometer at 660 nm) is now accepted as a precise measure of POC concentration in the ocean. The instrumentation is commercially available and is being increasingly applied across all ocean platforms. To date, there are now over 4 float-years of experience (2000 profiles to depths of 1000 m) with transmissometer based POC sensors. Biofouling degradation of the untreated optical surfaces of the POC sensors deployed on Carbon Explorers has been 0.5 to 1% transmission loss per month over one year. Precision of POC sensors has been improved, with beam attenuation coefficient precision better than 0.001 m^{-1} (POC precision of better than 0.02 μM).

Operational wide-scale deployment of POC sensors as part of a carbon observing system requires (1) standardization of optical specifics of these instruments across manufacturers (e.g. receiver acceptance angle) and a (2) calibration protocol that guarantees accuracy on first time deployment (current state of the art is 0.01 m^{-1}; desired $<0.001\ m^{-1}$). Improved accuracy and precision is critical in studies in the mesopelagic zone, where POC concentrations are low. Although there is no doubt of the usefulness of optical determination of POC and therefore a strong justification for operational deployment of transmissometers now as operational part of an ocean observing system, the community would be well served by a dedicated at-sea intercomparison of shipboard POC sampling methods and optical sensors.

PIC: A sensor for particulate inorganic carbon (PIC) with an operational range of <0.01 μM to >30 μM is reaching near operational and commerciallized status. The instrument detects the birefringent signal from calcium carbonate particles. Current uncertainties are the absolute calibration accuracy of the PIC sensor and its long term stability. The present uncertainties can only be resolved through comparisons between optically measured PIC and sampled PIC distributions at sea and through deployment on autonomous platforms such as the Carbon Explorer. The time scale for operational status is 2004.

POC and PIC flux: Optical methods for assessment of POC and PIC flux can be developed to exploit profiling floats and gliders. Profiling floats in particular spend much of their time drifting at depth. Such systems would operate during these times and have the potential to record carbon flux variability on timescales as fast as it occurs. Initial prototype systems are under development. Proof of such systems requires calibration against neutrally buoyant sediment trap systems capable of returning samples (Section 6.2 IV).

Dissolved O_2 sensors: Measurements of dissolved O_2 contain a wealth of information on marine biological and physical processes [e.g. Redfield, 1948; Levitus, 1994]. Over the past century, millions of discrete O_2 measurements have been made in the world oceans, using the Winkler titration method, and these data have been particularly useful in constraining seasonal productivity and air-sea gas exchange on hemispheric scales [e.g. Najjar and Keeling, 2000; Keeling et al. 1998]. Unfortunately, these analyses are labor intensive, and data coverage remains sparse in winter and at high southern latitudes. Existing *in situ* dissolved O_2 sensors tend to require frequent recalibration (electrolyte exposed to the water across a permeable membrane), or are expensive (gas-tension based sensor). Gas equilibrators, such as those used for measuring pCO_2, are less suited for ΔO_2 because of its lower solubility. A recent advance in the gas tension technology has been that of an ultra-stable dissolved pO_2/pN_2 sensor. This sensor is capable of operation at any depth and thus a profiling mode. DGT technology would benefit from effort to reduce response time (minutes to 10's of seconds) and size to permit this approach to be applied across all platforms.

Nutrient substrates: A reagentless NO_3- analyser has just been commercialized and shows promise for profiling applications. This ISUS instrument optically detects nitrate concentrations without reagents or laboratory testing, and efforts to down-power and miniaturize this system will benefit all platforms. Sensors for nitrogen components other than NO_3 either have high power requirements or have slow response times which would preclude most profiling applications. No technology exists for autonomous determination of dissolved Si of P in profiling mode.

Reactive micronutrients: There is no means to assess Fe directly in the water column, particularly ar the required precision of < 0.1 nM. However, iron limitation may be inferred indirectly via bio-optical measurements of photosynthetic competency (Fv/Fm). Optical instruments of this kind have found widespread use on ships and occasionally on moorings. Directed investment should made to enable adaptation of such instrumentation to profiling applications across all platforms.

Other Platform Issues

Autonomous, underway pCO_2 systems: Underway pCO_2 measurement systems are a mature technology and the surface VOS network, along with the existing time series stations, will form the backbone of the initial carbon observing system. At present, however, these systems lack a set of best practices and standards for intercomparisons, and are not autonomous and must be monitored by a qualified scientist or technician. The Japanese have recently developed a system that can be operated by a trained member of the ship's crew rather than employing a separate technician specifically to operate and maintain the underway system. This is an important step that has greatly reduced the operational costs, and will undoubtedly lead to an enhanced use of this monitoring technique.

Ship infrastructure: Future shipboard carbon cycle process studies require a significant upgrading of shore to ship telemetry of such data. Fast and uninterrupted ship to satellite links are also required for process studies which utilize autonomous vehicles.

9.2 Data Management and Data Availability

Data management within CCSP-oceans requires policies and infrastructure to: obtain the data; quality control incoming data sets; provide timely access to data; and ensure its long-term archival. The main elements of such a plan include establishing a data policy that requires investigators to submit data sets within a defined period of time, and providing the personnel and data systems necessary to provide quality data from acquisition through archival.

The types of data proposed within this CCSP-oceans plan include a wide variety of data (from standard hydrographic to biological processes) collected over a broad range of spatial and temporal scales (Table 5). Although this approach is essential for scaling from small spatial and temporal scales to regional/global and interannual scales, it presents significant challenges to data management.

Similar concerns were addressed at a recent data management planning meeting for LSCOP, which includes the repeart hydrography and VOS pCO_2 surveys (sections 4.1 and 4.2 of this document). This meeting produced a data management plan to establish a standardized scheme for data collection, quality control, rapid access, and archival (Feely and Sabine 2002), which was largely built on the experience gained form previous ocean data programs such as U.S. JGOFS and WOCE. The LSCOP plan provides firm groundwork for an ocean carbon cycle science data management plan, which can be modified to incorporate additional data from process studies and remote sensing.

Recommendations

The recommended components of a data management system include:

CO_2 Science Team. A committee of scientists and data managers should be established for developing standards for collection (both manual and automated), reporting and quality control of data from both field programs and automated sensors.

Data Management Group. This group is responsible for maintaining quality controlled data sets and providing timely access to data, preferably with internet-based public access. Ideally, the group will include representatives from a variety of institutions with experience at handling automated data acquisition and quality control, development of data acquisition systems, and long-term data archival.

Data Acquisition System. This primarily includes hardware and software for acquiring, storing, and delivering data in a variety of formats, and from a variety of sources.

Each of these components is necessary to facilitate timely access to quality data for data analysis, modeling and data assimilation. This is particularly important in the context of the North American Carbon Program, where there is a strong desire to integrate data from ocean, atmosphere and terrestrial studies. This calls for early collaboration with the atmospheric and terrestrial programs to establish data structure and metadata requirements, and other arrangements for streamlining data integration from these varied sources.

Details of a data management system can be derived from experience gained through the WOCE and US JGOFS programs (Glover et al., 2003). For example, the U.S. JGOFS program requires that data generated within the field programs (process study cruises) as well as within the synthesis and modeling phase of the study be submitted in a timely fashion (~12 months post-cruise), under specific guidelines of a data management policy. The U.S. JGOFS Data Management Office also maintains a data distribution system that incorporates many of the desired characteristics outlined in the CRP Strategic Plan (Nov. 2002 draft). The system allows access to data via the internet-based distributed data network, DODS/OPeNDAP (Distributed Oceanographic Data System; Open source Project for a Network Data Access Protocol). The data management plan within IOOS (Integrated Ocean Observing System), which is the U.S. component of GOOS (Global Ocean Observing System), is also based on OPeNDAP, which will ease the integration of oceanographic data from CCSP-oceans into IOOS. The U.S. JGOFS data system provides data visualization, data sub-setting, and data downloading in a variety of formats via a Live Access Server (LAS). Until recently, LAS-served data were restricted to gridded data. Due to combined efforts of the U.S. JGOFS Data Management Office, NOAA/PMEL, and the University of Washington through a grant provided within the U.S. JGOFS SMP, the U.S. JGOFS LAS now includes the capabilities to display and extract from discrete data (e.g. individual measurements) as well. Users of this system can display, subset, and download both discrete and gridded data, and have increased options for examining and downloading data from a variety of sources and formats.

Table 5. Temporal and spatial scales of various types of data included in this planning document.

Measurement	Spatial Resolution	Temporal Resolution (years)	Parameters
Repeat Hydrography	50 km profiles spaced every 50 km along discrete lines profiles typically sampled every 1–200 m depth	5–10 y	hydrographic parameters carbon system parameters various tracers, trace elements
VOS pCO_2 lines	5 km surface sampled every 5 km along discrete lines	0.125–0.2 y	Air and sea pCO_2
Process Studies	5–10 km profiles every 5–20 km along discrete lines	Varies typically one-time samples but can obtain higher frequency measurements while onsite	hydrographic parameters biological parameters (e.g. chlorophyll, zooplankton biomass) processes (e.g. particle flux, primary production)
Time Series	N/A discrete stations	0.083 y can obtain higher-frequency measurements while onsite	hydrographic parameters biological parameters (e.g. chlorophyll, zooplankton biomass) processes (e.g. particle flux, primary production)
Remote Sensing	1–100 km	0.003–0.083 y	See table 4 of Section 5.5
Drifters, floats, gliders, etc.	Varies	varies	hydrographic carbon system parameters biological paramenters

Maintaining high quality from the CCSP-oceans field program will require strong oversight by the Data Management Team. Much of the success of the previous ocean program is due to the efforts by data managers to track data from start to finish; i.e., from data collection, submission to the data system, quality control, distribution and archival. Every step of this process requires significant manpower, and continuous dialog between scientists and data managers (Figure 7).

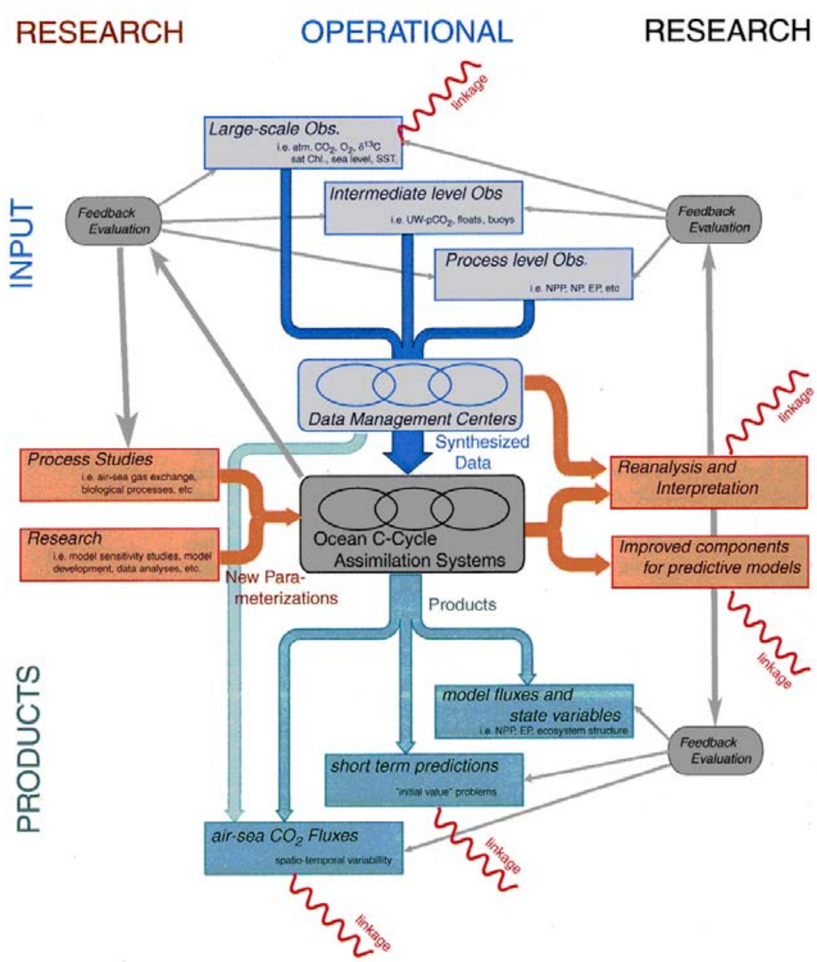


Figure 7: Data management schematic

9.3 International Cooperation and Linkages

The appropriate scale for investigation of the carbon cycle is global, and no single country can describe or quantify carbon cycling within its national boundaries without considering global processes occurring in the atmosphere and oceans. The vast majority of the ocean is a global commons, and its sheer size and often distant, inhospitable regions require nations to work together to develop a unified view of the ocean carbon cycle over a range of space and time scales.

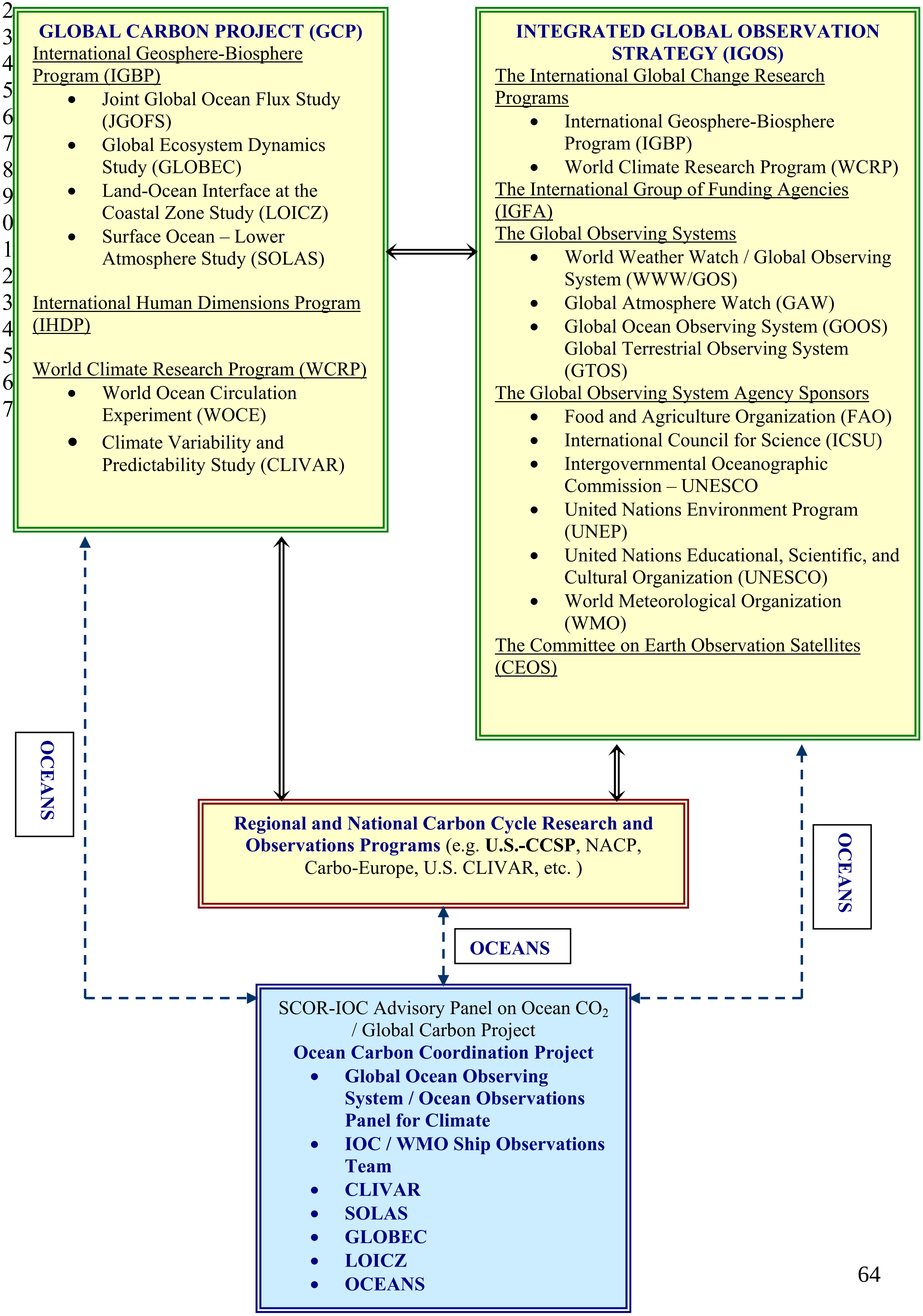
While we have begun to develop the capacity to monitor ocean carbon and to share this information with similar efforts in other countries, we are far from having a coordinated research or observation system, or aggregated data products on basin and global scales. A number of efforts are underway to establish international strategies for ocean carbon research and observations, and to identify mechanisms for the necessary communication and coordination among national and regional programmes.

The International Geosphere – Biosphere Program (IGBP), the International Human Dimensions Program (IHDP), and the World Climate Research Program (WCRP) have jointly developed the Global Carbon Project (GCP) to develop a framework for carbon cycle research that provides a comprehensive picture of the global carbon cycle, including both its biophysical and human dimensions, together with the interactions and feedbacks between them. (www.globalcarbonproject.org) The GCP will develop integrated core activities to identify and develop the key methods, models, knowledge of processes and interactions necessary to treat the global carbon cycle as a coupled human-natural system. These activities will focus on broad themes such as Patterns and Variability; Processes, Controls and Interactions; and Future Dynamics of the Global Carbon Cycle. Within these broad themes, the ocean carbon cycle will play a major role, and the GCP science framework highlights the research needed to eventually achieve this integrated understanding. The GCP will not develop discipline-level mechanisms to coordinate research and observations, but will instead seek partnerships with existing programmes.

In close collaboration with the GCP, the Integrated Global Observing Strategy (IGOS) Partnership (www.igospartners.org) has initiated the development of an Integrated Global Carbon Observation (IGCO) Strategy to provide an integrated plan for global carbon observations from satellite and earth-based systems. The IGOS Partnership (figure x) brings together the international global research programs, the global observing systems and their sponsor agencies, and national space agencies to develop thematic strategies that provide a framework for international cooperation and resource allocation. The IGCO strategy will provide a blueprint for an integrated global carbon observing system that will serve as a complement to the GCP research strategy.

These two international strategy groups, focusing both on integrated carbon research and observations, provides a framework for international cooperation to set research and observation priorities and to implement programs to meet these goals. To ensure compatibility and complementarity between the research and observation components, these two groups are working closely together. At the discipline-level (e.g., oceans, land, atmosphere) there are few international coordination mechanisms, and these two framework programs are working to develop the necessary partnerships to facilitate communication and coordination internationally. One of the first pilot projects of the GCP for international coordination activities will be a collaborative effort with the SCOR-IOC Advisory Panel on Ocean CO_2 (http://ioc.unesco.org/iocweb/co2panel) to provide a coordination forum for current and planned ocean carbon cycle studies and observations from a wide range of national, regional, and international programs. The SCOR – IOC Advisory Panel also serves as the ocean carbon advisory group for GOOS, the lead agency for the ocean component of the IGOS Partners' IGCO strategy.

Diagram of international framework for ocean carbon research and observations:



There is an immediate need for global-scale coordination of ocean carbon research and observations, since many national ocean programs for global carbon cycle research (including reoccupation of WOCE sections and new pCO_2 systems for a network of surface observations on ships of opportunity) have already begun or will be starting in the next couple of years. This pilot project will collate and build upon the existing web information and establish a model for coordination activities including periodic workshops to facilitate international collaborations. This is a difficult task that will require active solicitation for updates on the latest national plans and constant vigilance to find programs that have possible conflicts or potential for better collaboration. The potential benefit to the global community however is significant. The first workshop of the OCCP will be held in January 2003, focusing on planning coordination of underway carbon measurements made from ships of opportunity and on carbon and tracer measurements made on the repeat hydrographic sections of CLIVAR.

9.4 Workshops and Educational Outreach

Workshops are integral at every stage of the CCSP-oceans plan, from planning of field experiments, to analysis of results and dissemination of information. Workshops will be essential in planning not only field studies, but also for putting in place long-term plans for data management; communication and interaction with other carbon cycle science groups (both national and international); and mechansims for communicating with policymakers, educators, and the general public. Data analysis workshops will be designed to bring observationalists and modelers together to address specific problems. As discoveries are brought to light, additional workshops will be required to tackle new scientific challenges.

The draft CCSP Strategic Plan identifies four major needs that fall under the broad category of Reporting and Outreach (Chapter 13): 1) inventory of existing agency activities; 2) reporting and outreach for decisionmakers; 3) reporting and outreach for the public; and 4) outreach for K-12 education. The first of these constitutes the need to coordinate the various reporting and outreach activities of individual agencies, to eliminate duplicate efforts, and to focus on those efforts that are most effective. The second of these - reporting and outreach for decisionmakers - is an extremely important aspect of the CCSP because it influences policy making at regional, national and international scales. CCSP-oceans will provide research results to the Global Change Research Information Office for further dissemination to policymakers, and will participate in CCSP initiatives that facilitate reporting to both governmental and nongovernmental agencies.

Disseminating research findings to the public and to K-12 educators is recognized as a growing responsibility of carbon cycle research. As public awareness about climate change increases, so does demand for up-to-date information. There are several avenues for informing the community, including the media, the internet, and published materials. The oceanographic community has typically utilized all three modes, and improving communication to these groups will require using strategies specific to the target audience.

The media provides the most direct link between scientists and the community, but the effectiveness of how well the media conveys important scientific findings to the public is generally no better than how well the scientists communicate with the media. One way to improve this important link is to train scientists to be better communicators themselves. CCSP-oceans workshops will stress this aspect, perhaps by including a media liaison at meetings, providing guidelines on how to communicate results, composing fact sheets or press releases, and by closing workshops with a discussion of how best to communicate scientific results to not only the scientific community, but to the public in general.

Web-based education has become increasingly popular in K-12 classrooms. In concert with the call in the draft CCSP plan to coordinate and streamline outreach activities across the various agencies, CCSP-oceans will first research existing sites on the internet for the most effective sites, and will identify both duplicated efforts and gaps in what is currently available to K-12 educators. CCSP-oceans will work within the overall CCSP to maximize input within the streamlined K-12 outreach activities, by identifying new ideas that can be developed as new web sites, or incorporated into existing web sites. Finally, training of new scientists (PhD candidates and postdoctoral researchers) in ocean carbon cycle science will be promoted by reserving a certain percentage of slots at meetings and workshops for young scientists, and by encouraging their participation in nearly every aspect of the carbon cycle science plan.

9.5 Management Framework

The research components of the CCSP-Oceans program are synergistic and the ultimate success of the program in addressing the four overarching objectives detailed in section 4 depends upon the close coordination of the individual observational, process, and numerical studies. Past experiences with programs such as JGOFS and WOCE suggest that such integration requires explicit mechanisms be put in place at a variety of levels from the inception of the program. Because of the changing nature of technology and scientific understanding, the structure of the CCSP-Oceans program should remain flexible, with a mixture of research projects ranging in scope from individual PIs to mid- to large-scale multi-investigator observational networks and field expeditions. The modeling, remote sensing, and field components should proceed hand and hand, facilitated by requiring the formulation of multi-PI, interdisciplinary teams including scientists working on models and satellite data for the larger projects, particularly the process studies. An annual PI meeting series should be initiated to facilitate the interactions among researchers, and program planning and data management offices should be established. Finally, the overall scientific oversight and guidance of the program should be under the direction of a scientific steering committee representing the diversity of the multi-agency nature of the program.

The planning efforts for different aspects of ocean carbon research have progressed at different rates, as illustrated by the maturity (and funded projects) for some of the observational components (Repeat Hydrography; VOS pCO_2 survey) relative to other elements described above. A key next step will be to refine the specific planning for the implementation of the coastal observing network (in conjunction with the NACP) and the North Atlantic and North Pacific process studies.

During the phase I period of CCSP-Oceans (2005-2009), a variety of other national and international oceanographic programs will carry out relevant studies in the North Atlantic, North Pacific and Southern Ocean. The CCSP-Oceans should maintain ties with these programs (e.g., CLIVAR, RIOMAR) to ensure that the program capitalizes on potential leverage opportunities in planning CCSP-Oceans field efforts. For example, the Southern Ocean CLIVAR subcommittee has recommended a program in the Southern Ocean to better constrain momentum, heat, moisture and gas transfer rates in regions of very high wind speed. At the time of this writing, at least two proposals to study marine ecosystems and the ocean carbon cycle are being prepared for submission to the European Framework 6. One of those proposals focuses specifically on the Southern Ocean whereas another is global in extent, but with a clear interest in the Southern Ocean. Although it is too early to say if either of these programs will be funded, CCSP-Oceans must take account of those efforts in designing any future US program to study the carbon cycle in the Southern Ocean.

Recommendations

- An open ocean carbon cycle science workshop should be held in the Fall/Winter of 2003/2004 to: bring together currently funded Pis from the repeat hydrography, VOS pCO_2, and HOT and BATS time-series; build broad community support for the proposed CCSP-Oceans program; refine the program elements, specific recommendations and cost estimate; and develop more comprehensive plans for the individual process study components.

- The CCSP-Oceans interim implementation committee should be transitioned into a more formal scientific steering committee with oversight of the ocean carbon components of the CCSP. The committee should include representation from both active CCSP-Oceans PIs and the scientists from broader research community and should report to the CCSP Scientific Steering Group and Interagency Working Group.

- Centralized planning and data management offices should be established for the CCSP-Oceans program to coordinate and facilitate community activities.

10 Scientific Products and Payoffs

Anticipated scientific products and payoffs from CCSP-Oceans are summarized in Table 6 along with a list of program elements that would contribute to each product. As shown in the table, each of the major products and payoffs of CCSP-Oceans are achievable only by combining results from two or more implementation elements. The specific recommendations and rough cost estimates for Phase-1 of the CCSP-Oceans program are summarized in Table 7.

Table 6 CCSP-Oceans: Products, Payoffs, and Program Elements

-Temporal evolution and lateral transport of ocean natural and anthropogenic CO_2, nutrients, oxygen, DOM, and trace metals (e.g., constrain basin-scale decadal changes of anthropogenic carbon inventory to +/- 20%)	
Repeat hydrography surveys	(section 5.1)
Open-ocean time-series	(section 5.3)
Numerical Modeling	(section 8)
-Air-sea CO_2 flux basin-scale to global patterns, seasonal to inter-annual variability, and climate sensitivity (e.g., constrain North Atlantic and North Pacific fluxes to +/-0.2 Pg C/y)	
VOS pCO_2 surveys	(section 5.2)
Open-ocean time-series	(section 5.3)
Remote sensing	(section 5.5)
Gas exchange process studies	(section 6.3)
Data assimilation and hindcast modeling	(section 8)
-Seasonal to interannual variability and secular trends for upper ocean carbon cycling, ecosystem structure, primary and export production, and subsurface carbon dynamics.	
Open-ocean time-series	(section 5.3)
Remote sensing	(section 5.5)
Upper water column process studies	(section 6.1)
Mesopelagic process studies	(section 6.2)
Data assimilation and hindcast modeling	(section 8)
-North American coastal ocean and continental margin air-sea CO_2 fluxes, land-ocean and coastal open ocean carbon exchange, and biogeochemical cycling	
VOS pCO_2 surveys	(section 5.2)
North American coastal observing network	(section 5.4)
Continental margin process studies	(section 6.3)
Gas exchange process studies	(section 6.4)
-Physical, chemical, and biological controls on present and future marine ecosystems and ocean carbon cycle including biogeochemical responses to and feedbacks on climate change	
Upper water column process studies	(section 6.1)
Mesopelagic process studies	(section 6.2)
Continental margin biogeochemistry	(section 6.3)
Numerical modeling	(section 8)
-New suite of tested in situ, remote sensing and numerical tools for observing and studying the ocean carbon system	
Remote sensing	(section 5.5)
Air-sea gas exchange	(section 6.3)
Numerical modeling	(section 8)
Sensor and platform development	(section 9.1)
-Communication of research findings and decision support tools to stakeholders (scientific community, policy makers, resource managers, students, general public)	
Data management	(section 9.2)
International coordination and linkage	(section 9.3)
Workshops and education outreach	(section 9.4)
Scientific oversight and management	(section 9.5)

Table 7 Specific Recommendations and Cost Estimates for CCSP-Oceans Phase-1 (2005-2009)

Repeat Hydrography (section 5.1)	[$3.5-4 M/yr]
base program [funded NSF/NOAA; 2003-2008]	
collection and post-cruise analysis of other species (e.g. ^{14}C)	$2.0 M/yr
VOS pCO_2 Survey (section 5.2)	[$1-2 M/yr]
base program [funded NOAA; 2003-2005]	
additional VOS lines, sampling & underway pCO_2 on UNOLS vessels	$1.3 M/yr
Open-ocean time-series (Section 5.3)	$3.0 M/yr
continuation/augmentation of BATS, HOT, and EqPac	
carbon measurements at North Pacific and Atlantic sites	
North American coastal observing network (section 5.4)	$3-4 M/yr
coastal mooring and CO_2 flux sites	
ship-based transects	
coastal remote sensing algorithms development/validation	
Remote sensing (section 5.5)	$3-4 M/yr
ocean color and new bioptical products development and validation	
evaluation of techniques for seasonal air-sea CO_2 flux	
synthesis and analysis of remote sensing data	
Upper-water column (section 6.1) and Mesopelagic (section 6.2)	$6-9 M/yr
targeted field and laboratory programs	
time-series continuation and augmentation	
development/testing of new biogeochemical/ecosystem techniques	
Continental margin biogeochemistry (section 6.3)	$2-3 M/yr
intensive process field programs at coastal mooring sites	
coastal/open ocean transport studies	
land-margin-open ocean integration	
Air-Sea gas exchange (section 6.4)	$2-3 M/yr
gas exchange process studies	
long-term CO_2 flux observations	
remote sensing algorithm development	
Southern Ocean synthesis and pilot studies (section 7)	$2-3 M/yr
historical data synthesis	
underway pCO_2 and moored O_2	
model development and intercomparison	
Synthesis and numerical modeling (section 8)	$3-4 M/yr
carbon data centers (w/ data management)	
network design studies	
regional and global ocean biogeochemical models	
reconciliation of ocean and atmosphere CO_2 flux estimates	
hindcast simulations (1950s to present)	
pilot data assimilation studies	
prognostic ocean carbon and carbon-climate projections	
model tools for assessments and ocean carbon management	

Table 7 Specific Recommendations and Cost Estimates for CCSP-Oceans Phase-1 (2005-2009) (cont.)

Sensor and platform development (section 9.1)	$3-4 M/yr
in situ carbon system sensors	
integration with autonomous platforms	
reference standards	
Data Management (section 9.2)	$1-1.5 M/yr
data processing and quality control	
distribution and archival	
data Integration at International level	
International coordination and linkages (section 9.3)	$0.25 M/y
Workshops and educations outreach (section 9.4)	$0.5 M/yr
Management framework (section 9.5)	$0.5 M/yr
planning office and steering committee	

Note: budget estimates provided for existing and phase 1 (2005-2009) elements of the CCSP-oceans program. Ongoing and recently funded elements of the program are marked accordingly in brackets [$ M/yr].

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12 Acronyms and Glossary

Aquarius	NASA ocean salinity mission selected for further development in 2002 under the Earth System Science Pathfinder (ESSP) program
AVHRR	Advanced Very High Resolution Radiometer (NOAA)
GLI	Global Imager (Japan.ADEOS-II)
MERIS	Medium Resolution Imaging Spectrometer (Europe, Envisat)
MODIS	Moderate Resolution Imaging Spectroradiometer (US, Terra & Aqua)
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
SeaWiFS	Sea-viewing Wide Field-of-View Sensor (NASA & ORBIMAGE)
SeaWinds	Scatterometer on ADEOS-II
POLDER	Polarization & Directionality of the Earth's Reflectance (France, ADEOS-II)
QuikScat	Scatterometer mission (US)
VIIRS	Visible and Infrared Imaging Suite (US, NPP and NPOESS)