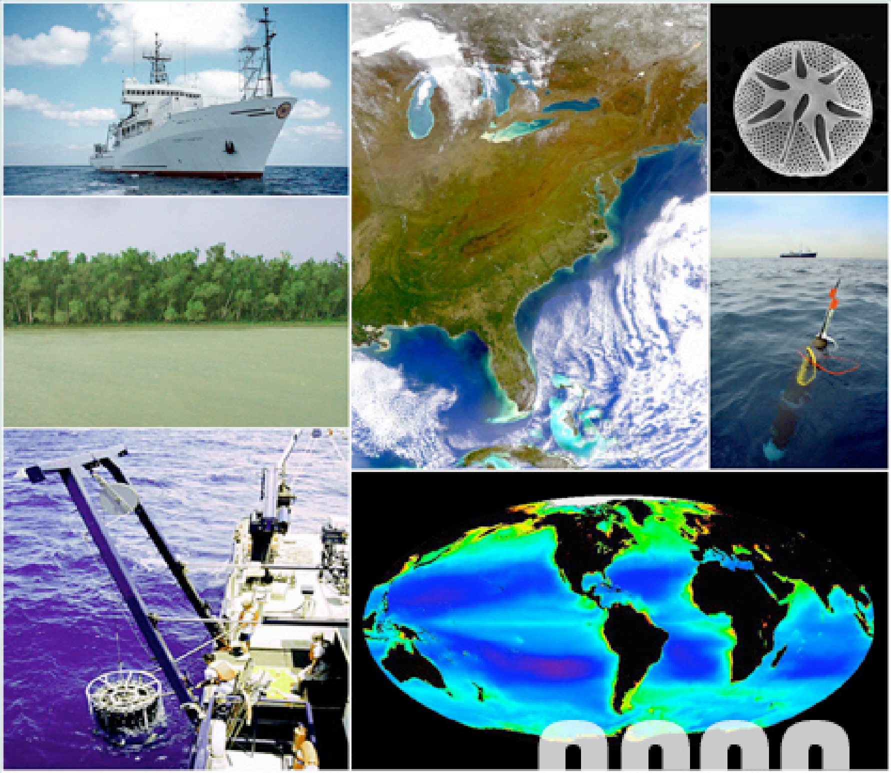
Ocean Carbon and Climate Change

An Implementation Strategy for U.S. Ocean Carbon Research



OCCC

Prepared for the
U.S. Carbon Cycle Science Scientific Steering Group
and Inter-agency Working Group
by the
Carbon Cycle Science Ocean Interim Implementation Group

Scott C. Doney
chair and editor

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1 Summary

The ocean component of the global carbon cycle is a key component of the climate system, regulating on annual to millennial time-scales 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 strategy 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 strategy for an **Ocean Carbon and Climate Change (OCCC)** program is designed as an ocean component of the U.S. Global Change Research Program Carbon Cycle Science Program and the U.S. Climate Change Science Program. 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 U.S. Carbon Cycle Science, we highlight four fundamental science questions:

1. What are the global inventory, geographic distribution, and temporal evolution of **anthropogenic CO_2** in the oceans?
2. What are 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 organic and inorganic 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, and air-sea gas exchange.
- Integrating field observations, remote sensing, **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, cross-disciplinary and international cooperation, workshops, education and outreach, contributions to national carbon assessments, and ongoing scientific oversight and coordination.

A phased approach is proposed for a decadal-scale research program. Phase 1 of OCCC will accelerate technology development, initiate North American and global carbon observing systems (e.g., CLIVAR/Carbon Repeat Hydrographic Survey, VOS surface pCO_2 lines), test specific climate-change hypotheses through targeted process studies in the context of existing open-ocean and continental margin time-series stations, and establish time-series stations and process studies in new marine biomes. A regional focus will be placed in Phase 1 on the North Atlantic and North and Equatorial Pacific in conjunction with the North American Carbon Program. Southern Ocean synthesis and pilot studies will also be carried out followed by a full Southern Ocean field effort in Phase 2. Particular emphasis is placed in Phase 1 on technology development and field testing of new biogeochemical techniques, development of reference materials to assure data comparability, whole ecosystem manipulation experimental approaches, remote sensing algorithms, data assimilation, and autonomous sensors and platforms that have the opportunity to revolutionize how ocean carbon research is conducted and will provide the capability to measure important properties over large sections of the ocean on an almost continual basis. While the OCCC will encompass a wide breadth of ocean biology, chemistry, and physics research, the program will also promote linkages and synergies with related ongoing oceanographic, climate, and carbon cycle programs (e.g., CLIVAR, OCEANS.US, ORION, NACP, IGBP IMBER, SOLAS, and Global Carbon Project) to address the full range of scientific elements relevant to marine carbon dynamics and the climate change question.

Anticipated scientific products and payoffs from OCCC are summarized as follows:

- Temporal evolution and lateral transport in the ocean of natural and anthropogenic CO_2, nutrients, oxygen, dissolved organic matter, and trace metals (e.g., constrain basin-scale decadal changes of anthropogenic carbon inventory to +/- 20%)
- Basin-scale to global patterns, seasonal to inter-annual variability, and climate sensitivity of air-sea CO_2 flux (e.g., constrain North Atlantic, North and Equatorial 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 dynamics 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 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 were essentially 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 background, a complex system involving the ocean, atmosphere and land domains and the fluxes among 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 on time-scales of thousands to tens of thousands of years (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 dynamics (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:

- Goal 1: Quantify and understand the Northern Hemisphere terrestrial carbon sink;
- Goal 2: Quantify and understand the uptake of anthropogenic CO_2 in the ocean;
- Goal 3: Determine the impacts of past and current land use on the carbon budget;
- Goal 4: Provide greatly improved projections of future atmospheric concentrations of CO_2;
- Goal 5: Develop the scientific basis for societal decisions about management of CO_2 and the carbon cycle;

several of which have significant ocean components. Goal 1, for example, 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 in order to close the carbon budget over North America. 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. Goal 5 requires significantly better scientific understanding of the potential efficacy and impact of ocean carbon management strategies such as direct CO_2 injection and trace-metal and nutrient fertilization. Achieving these goals requires an integrated oceanic program involving strategies for observations over a wide range of temporal and spatial scales combined with hypothesis-testing experimental studies and model development.

The objective of this document is to outline an implementation strategy for an ocean carbon component, which we term the **Ocean Carbon and Climate Change** (**OCCC**) program, for the U.S. Global Change Research Program Carbon Cycle Science Program (http://www.carboncyclescience.gov/) and the U.S. Climate Change Science Program (Mahoney, 2003; http://www.climatescience.gov/). An Interim Implementation Group was formed in July, 2002 by the U.S. Carbon Cycle Scientific Steering Group and Inter-agency Working Group. The specific charge to this group was to develop integrated, cross-agency implementation ideas; facilitate implementation and coordination of existing and emerging U.S. ocean carbon research; and maintain links to other components of the U.S. Carbon Cycle Science, climate and ocean physics, and international programs.

The OCCC program builds upon a strong history of coordinated U.S. and international oceanographic research, in particular the Joint Global Ocean Flux Study (JGOFS; http://usjgofs.whoi.edu/; http://www.uib.no/jgofs/jgofs.html) and the World Ocean Circulation Experiment (WOCE; http://www.soc.soton.ac.uk/OTHERS/woceipo/ipo.html) conducted in the late 1980's and 1990's. JGOFS, WOCE and related programs such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS; http://seawifs.gsfc.nasa.gov/SEAWIFS.html) satellite ocean color project provide for the first time a truly global-scale perspective on the ocean carbon dynamics and ocean circulation (McClain et al., 1998; Siedler et al., 2001; Fasham, 2003). WOCE and JGOFS, however, were primarily focused on characterizing the current state of the ocean, and critical questions remain to be answered regarding how the ocean is evolving in time now and into the future under global climate change. A significant research investment is required if we are to have better confidence in our predictions of the future behavior of the marine carbon system.

This document draws heavily on a series of U.S. and international ocean carbon 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 (EDOCC, 2001); U.S. SOLAS-Surface Ocean Lower Atmosphere Study (Wanninkhof, 2002); LSCOP-Large-scale CO_2 Observing Plan: In situ Oceans and Atmosphere (Bender et al., 2002); an international GOOS-Global Ocean Observing System report on ocean carbon (Doney and Hood, 2002); the IGOS Ocean Theme document (Lindstrom, 2000); the RioMar report (McKee, 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 system, 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 components of the 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 science plan and implementation strategy for the U.S. North American Carbon Program (NACP) (Wofsy and Harriss, 2002; Denning et al., 2004) and the Carbon Data Assimilation workshop report (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, Gruber, 1998; Sabine et al., 1999, Sabine et al., 2002), ocean forward and inverse models (Sarmiento et al., 2001; Gloor et al., 2003), and combined use of atmospheric oxygen and CO_2 records (Keeling and Shertz, 1992, Keeling et al., 1996; Bopp et al., 2002). 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 lateral 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). The study of purely physical transport processes in the ocean is a huge endeavor in itself and is arguably further along than the study of ocean ecosystems and their effect on the carbon cycle. Dedicated programs to study ocean physics and its relation to climate variability, especially the World Climate Research Programme on Climate Variability and Predictability (CLIVAR), are underway and are cognizant of the importance of carbon transport in the study of climate change. The focus here is on the biogeochemical components of the marine carbon system, which plays a large role in controlling the inventory and spatial and temporal gradients of DIC within the ocean.

Previous geochemical and biogeochemical research programs such as GEOSECS, JGOFS and WOCE have elucidated the basic pattern of the ocean carbon system. Key features 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 matter and particulate $CaCO_3$ 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 as part of JGOFS and related research programs (Fasham et al., 2001; Fasham, 2003) and the recent availability of satellite ocean color measurements (McClain et al., 1998; 2002a) have greatly improved our understanding of 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., 1999; 2002). The general magnitude and mechanisms of mid-latitude variability signals are less clear (LeQuere et al,, 2000; 2003), but significant year to year variability is evident in the subtropical Bermuda Atlantic Time-Series Study (BATS) and Hawaii Ocean Time-Series (HOT). At 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.

Large annual and interannual variation in pCO_2 is also observed in tropical regions. Monthly pCO_2 data collected since 1996 by the Carbon Retention In A Colored Ocean (CARIACO) time series shows average pCO_2 values in the southern Caribbean Sea are higher than typical surface open ocean values, in spite of very high primary productivity and sinking particulate organic carbon flux observed there along that continental margin. Seasonal fluctuations in surface pCO_2 in that region are also strongly modulated by rivers. River discharge leads to pCO_2 minima, suggesting that the Amazon, Orinoco, and other major and minor rivers have impacts on surface pCO_2 in coastal areas and adjacent ocean waters that have not yet been examined.

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 may 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 al., 1996; Doney and Sarmiento, 1999). Potential effects include:

- decreased calcification from lower pH and CO_3^{-2} 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., 2003).

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 of measuring important properties over large sections of the ocean on an almost continual basis. Therefore the development and field validation of such instruments and techniques is highlighted as a key element in the OCCC implementation strategy.

4 Objectives and Implementation Strategy

While the overarching Carbon Cycle Science goals described in section 2 (Sarmiento and Wofsy, 1999) provide general guidance for the development of the OCCC program, more focused scientific questions must be articulated in order to design a research implementation plan. A major common question that runs through community ocean carbon planning documents is what are the past, present and future net oceanic uptake rates of CO_2? To address this problem, one must have a good quantitative description of the modern carbon system (inventory, air-sea fluxes, non-atmospheric inputs such as rivers, groundwaters and coastal tidal exchange 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 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 store 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 are 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, microorganism biomass, pigments, community structure, etc.); 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 are 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 and potential secular trends; 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 organic and inorganic 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/H/O/S/Si) 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. Focused, multi-disciplinary process studies are needed to address these issues, delineating the physical, chemical and biological factors governing present biogeochemical cycling and their sensitivity to global change.

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 a more thorough understanding of the feasibility, overall climate effectiveness, environmental impacts, stability and sequestration time scales are needed.

OCCC is timely because there is an immediate societal need for better, quantitative understanding of ocean climate responses and because of the opportunities for significant progress from the convergence of rapidly evolving technologies (e.g., satellites, in-situ sensors and autonomous platforms, deliberate field perturbation studies, genomic techniques, and data assimilation) and emerging scientific paradigms.

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-ocean ecosystems and air-sea CO_2 flux to inter-annual climate variability,

biogeochemical cycling in the mesopelagic zone, coastal ocean carbon dynamics and Southern Ocean dynamics. These studies will elucidate mechanistic relationships, improving the reliability of future climate predictions.

- Integrating field observations, remote sensing, **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 approach is proposed for a decadal-scale OCCC research program that builds on the technological and intellectual accomplishments of WOCE, JGOFS and other programs conducted over the preceding fifteen years. In Phase I of OCCC, the primary focus will be the North Atlantic and North and Equatorial Pacific in conjunction with the network of existing ocean carbon observations (coastal and open-ocean time-series, Volunteer Observing Ship transects, etc.) and the North American Carbon Program. A timeline of OCCC Phase 1 activities is presented in Figure 1, indicating the sequence and proposed start dates for different OCCC program elements. While the overall structure and relationships among research components has been determined, the exact details and start dates may evolve though time following community implementation workshops and discussions among the new OCCC Scientific Steering Committee and federal agency program managers.

The timing of specific OCCC Phase 1 activities is determined by opportunities for making rapid scientific advances with current capabilities and the investment required early in the program in the appropriate infrastructure and technology to fulfill more ambitious objectives in the future (Figure 1). The following key enabling and research activities are identified for the first year of the program: establish a Scientific Steering Committee and OCCC Planning and Data Management Offices (Sections 10.1 and 10.6); conduct implementation workshops on specific OCCC components (Section 10.4) and coordinate with national and international programs (Sections 10.2 and 10.3); accelerate technology development on new biogeochemical techniques and chemical/biological reference standards, autonomous sensor systems, platforms, communication methods, and satellite remote sensing (Section 9); and maintain and enhance on-going open-ocean and coastal time-series stations (Sections 5.3 and 5.4), satellite remote sensing (Section 5.5), and the recently initiated Repeat Hydrography and Volunteer Observing Ship pCO2 Surveys (Sections 5.1 and 5.2).

Over the following several years, the OCCC program will: initiate an on-going synthesis and modeling component including synthesis of new and historical data and experimental design studies (Section 8); deploy individual and mid-size process studies in the context of existing time-series sites (Section 6); begin elements of the North American carbon observing system (Section 5.4); and establish additional time-series in new subpolar, tropical/equatorial, and/or continental margin environments (Section 5.3 and 5.4) as the ground work for an integrated, large-scale Northern Hemisphere process studies culminating OCCC Phase 1 (Section 6). Pilot studies in the Southern Ocean conducted from ships and platforms of opportunity and deployment of exploratory time-series stations are also anticipated during OCCC Phase I (Section 7). Phase II of the OCCC program, which will be developed in greater detail over the course of the next several years, will consist of a full Southern Ocean field effort including new autonomous technologies developed in Phase 1, enhanced observing system capabilities, and targeted process studies.

The OCCC Phase I focus on the North Atlantic and North and Equatorial Pacific Oceans provides an immediate, strong linkage to the North American Carbon Program and builds on the existing time-series research sites such as BATS, HOT, CARIACO, and Monterey Bay. In addition, the emerging Integrated Ocean Observing System, OCEANS.US, and ORION ocean observatory initiatives will provide numerous opportunities to develop research partnerships and collaborations in both the coastal and open-ocean domains. The technology developments associated with the proposed new ocean observatories parallel the developments required to advance our research capabilities in remote areas such as the Southern Ocean. Carbon research conducted adjacent to North America and in the high nutrient, low chlorophyll areas of the Pacific also provide the foundation for assessing potential carbon mitigation strategies such as direct injection of carbon dioxide into deep waters and surface fertilization.

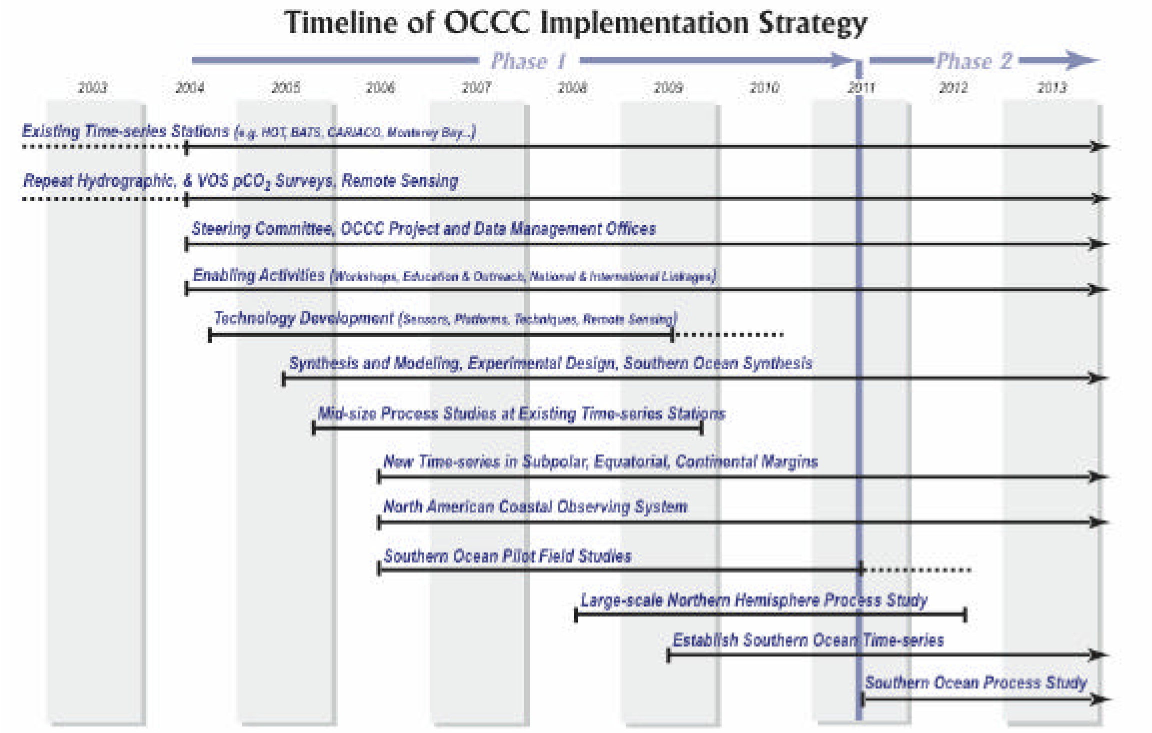

Figure 1: Proposed timeline for Ocean Carbon and Climate Change Phase 1

It must be emphasized that processes that are important for quantifying the marine carbon system and variations in ocean carbon storage must be observed on a wide range of space and time scales. This requires the combined use of multiple sensors and platforms, often operated or supported through different agencies. Strong interagency cooperation and collaboration will be required to achieve the goals of this program.

The following sections describe individual elements of this program, a number of which 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 infrastructure. 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 (OCCC 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 OCCC 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 OCCC (Section 6). Ocean observing systems are emerging in a number of oceanographic contexts (Lindstrom, 2000; 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 10 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 system. 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 8), 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 9.1). 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.

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 fluorometers, radiometers, and transmissometers will provide estimates of biological (e.g. chlorophyll and particulate organic matter) stocks and distribution.

- A comprehensive upper ocean observing system on board research and volunteer observing ships (VOS) to determine the air-sea flux of CO_2 and its interannual variability, and to understand the biogeochemical properties and rate processes that determine the partial pressure of CO_2 at the surface. Relevant measurements include continuous sea surface pCO_2 analyses, concentrations of bioactive species, the isotopic composition of dissolved inorganic carbon, oxygen and nitrogen, and other underway properties, some of which could include shore-based analysis of archived samples. In some cases it will be appropriate to limit the analyses to measurements that can be maintained by the ship's crew, while in other cases it will be appropriate for dedicated scientific participants, allowing measurement of a broader spectrum of properties.

- 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 that are not easily accommodated on transects, e.g., primary production.

- Coastal time series stations and seasonal surveys to quantify the sources, sinks, and lateral fluxes of carbon in the continental margin regions off 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 CO_2 flux and biological state variables and rates and application of existing and planned satellite measurements as well as additional aircraft observations.

- Atmospheric observations of the O_2/N_2 ratio of air, a property that reflects seasonal and annually averaged ocean carbon fluxes and their interannual variability. O_2/N_2 ratios are our primary tool for constraining basin scale net oceanic production in almost real time. These measurements should be enhanced by Ar/N_2 measurements that reflect the summertime stratification, and wintertime ventilation of the oceans, processes that are integral to understanding the carbon fluxes.

- 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.

5.1 Large Scale Ocean Repeat Hydrographic Survey

The overarching goal of the Repeat Hydrography Survey, a joint collaboration between the U.S. Carbon Cycle and CLIVAR programs begun in 2003, 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; see also http://ushydro.ucsd.edu/). 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 JGOFS/WOCE global carbon survey. 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 JGOFS/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 the 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. 2), most of them reoccupations of WOCE Hydrographic Program sections, which will be resampled 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 the isotopes of carbon, nitrogen, and O_2 (currently not supported), TOC (total organic carbon), total organic nitrogen (TON), and total organic phophorus (TOP)(currently not supported). Standards will be used for measurement of all parameters. In addition to the hydrographic (including: temperature, salinity, oxygen, nutrients, LADCP) and carbon system parameters, 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 the natural and anthropogenic changes to ocean carbon concentrations.

Additional tracer and biogeochemical measurements will be added to the Repeat Hydrography program on a transect by transect basis. Some of the tracers to be measured reveal mixing over the critical longer time scales; and some help identify current short-term invasion rates for comparison with older data. Oxygen isotope tracers $^{17}O/^{16}O$ and $^{18}O/^{16}O$ of dissolved oxygen, for example, interpreted in the context of mixing models, allow one to characterize the interaction of net production, gross production, respiration and mixing that give rise to observed nutrient distributions and rates of biological production. Trace metals, including Fe and Zn, and bio-optical parameters will also be measured in the upper water column. Trace metal limitation is indicated as a key factor governing marine productivity and carbon cycling, but the global distributions of trace metals are not well known at the present. The Repeat Hydrography Program and related, proposed projects such as GEOTRACES (http://www.ldeo.columbia.edu/geotraces/), will provide a basic, first order characterization of the large-scale patterns.

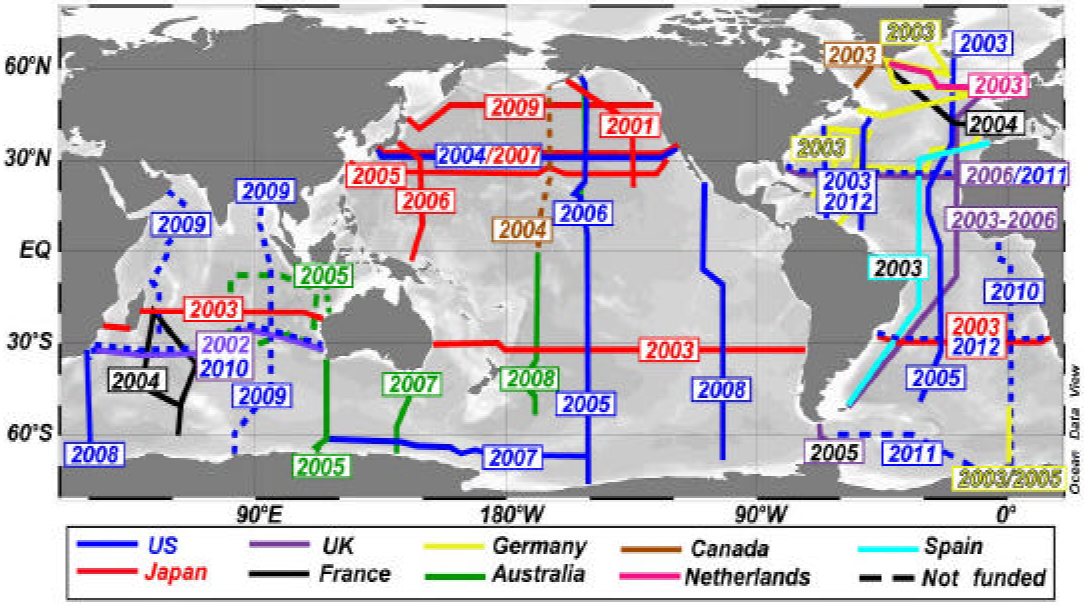

Figure 2: Proposed national and international Repeat Hydrography sections for the FY 2003-2012 period.

Station spacing on the proposed Repeat Hydrography 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.

5.2 Volunteer-Observing-Ship (VOS) pCO_2 Surveys

One of the major objectives of the U.S. Carbon Cycle Science program 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, much less on their origins.

The goal of the U.S. Volunteer Observing Ship (VOS) pCO_2 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) and to achieve a mechanistic understanding (and ultimately predictive understanding) of the biogeochemical rate processes giving rise to the observed sea surface pCO_2 distributions. The scientific objectives are: a) add data acquired during the project to the extensive database spanning the past 40 years to improve the seasonal climatological distribution of surface water pCO_2 (Takahashi et al., 2002); b) in conjunction with CARINA (Carbon in the Atlantic Ocean; http://www.ifm.uni-kiel.de/fb/fb2/ch/research/carina/) and the North Pacific Marine Science Organization PICES (http://www.pices.int) 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 basin wide air-sea CO_2 fluxes to ±0.2 Pg C yr-1. In addition to the insight they will add with respect to ocean regional and global efforts, the underway CO_2 measurements will improve the accuracy of air-sea flux measurements for the NACP 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.

Surface data on other bioreactive tracers can be collected with a modest additional effort as part of an underway pCO_2 survey and can provide important constraints on the rates of oceanic biological and physical fluxes beyond that available from pCO_2 alone. Recent analytical advances have enhanced our abilities to measure the stable isotope distributions of carbon, nitrate, O_2, and SiO_2, particularly important because isotopic tracers allow one to separate the influence of competing processes such as photosynthesis and respiration, consumption and production, nutrient utilization and resupply by mixing, and production (or consumption) and gas exchange. By combining isotopes and concentrations, the absolute values of the competing rates can be determined. Samples can be easily collected at sea, and large numbers of samples can be analyzed on shore. A well organized program involving the analysis of concentrations and isotopes will allow us to dramatically extend our knowledge of bioactive fluxes, their interannual variability, mediating processes, and their quantitative influence on sea surface pCO_2.

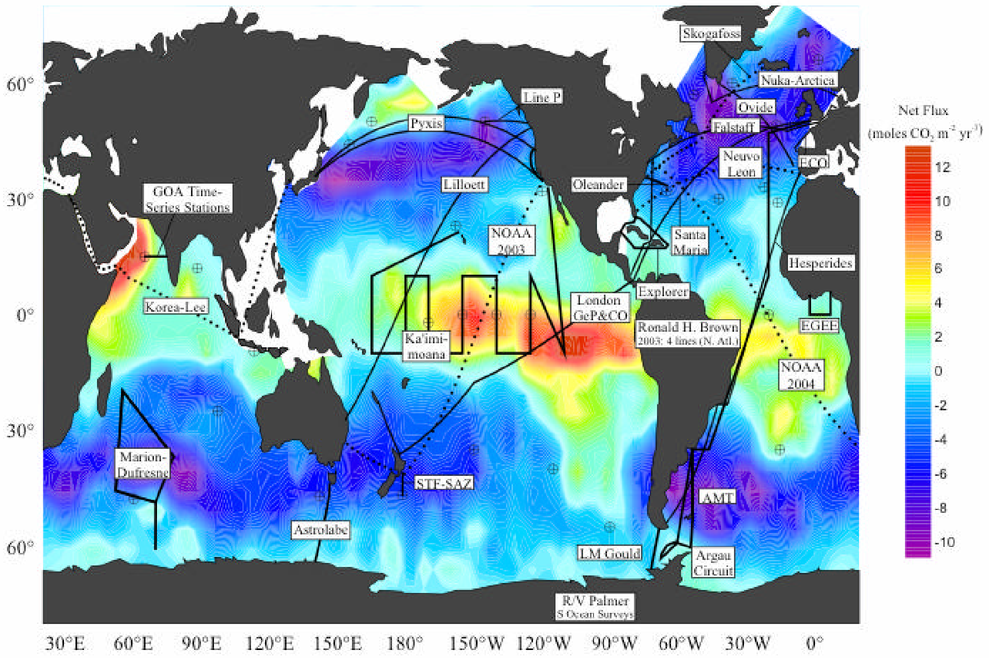

Figure 3: The pCO2 VOS lines currently maintained by US and International partnerships in the world oceans. The Atlantic partners will coordinate their efforts through the Global Carbon Project and CAVASSOO and the Pacific partners will coordinate their activities through the activities of Global Carbon Project and PICES Working Group 17. The locations of present and planned time-series stations are also shown.

Recommendations

Through support from NOAA and the NSF Office of Polar Programs, surface water pCO_2 measurements are currently performed routinely on the NOAA ships *Ronald H. Brown* and *Ka'imimoana* and the *RVIB Nathaniel B. Palmer* and *ARSV Laurence M. Gould* that support the U.S. Antarctic Program. In addition, NOAA has funded a U.S. Volunteer Observing Ship pCO2 Survey program for 2002-2008. Five surface water pCO_2 systems are being placed on commercial vessels in the North Atlantic and North Pacific participating in the VOS XBT network of the Global Observing Ocean System (GOOS) starting in 2004 (http://www.aoml.noaa.gov/ocd/pco2/). The VOS pCO_2 survey 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 track lines. 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 and Equatorial Pacific and North Atlantic during periods of OCCC process studies or the NACP) or for an expanded measurement suite. As currently planned and funded, the US VOS pCO_2 Survey will cover the following lines:

Atlantic Ocean

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. 3).

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. 3). 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. 3), 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. 3). 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.

Pacific Ocean

Los Angeles to New Zealand This line, with ports of call in Los Angeles, Auckland, Brisbane, Melbourne, Sidney, and Honolulu (Fig. 3), 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* services 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. 3).

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 Nathaniel B. Palmer The LDEO group is presently running a surface water pCO_2 program aboard the *RVIB Nathaniel B. 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.

Underway sampling on UNOLS vessels
Instrumentation 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 offering higher resolution surveys of specific regions. Routine underway pCO_2 measurements on UNOLS vessels will also 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 system and for determining the physical and biological mechanisms controlling the dynamics. 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 new chemical and biological techniques and autonomous sensors as well as serving 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 led 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., Chavez et al., 1999; Dickey, 2003) (Section 9.2). 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.

Time-series also play a key role in the OCCC strategy for integrated process studies (Section 6), which will be conducted at existing and new time-series sites that operate for a minimum duration of about 5-years. When feasible, exploratory ship-based and autonomous time-series components will be initiated before a process study begins, and some portion of the time-series measurements would continue following the completion of each process study as part of its legacy.

The specific design of the OCCC time-series network will be carried out in cooperation with other oceanographic and climate field and in particular to leverage opportunities of adding biogeochemical instrumentation to moorings/sites in place for other studies. For example, strong potential synergies exist with an international effort advocating and organizing moored time-series measurements of air-sea fluxes and physical climate variables (http://www.oceantimeseries.org). The U.S. NSF Division of Ocean Sciences is developing a major infrastructure project on ocean observatories called ORION (http://www.orionprogram.org). An anticipated outcome of the program is that a number of moorings (some like traditional surface moorings, some with power and real time high bandwidth communication) will be made available as community facilities that could be utilized as part of OCCC.

Recommendations

The emphasis during the first part of OCCC Phase 1 is on maintaining existing open-ocean Northern Hemisphere subtropical and equatorial stations and establishing new sites or augmenting ongoing time-series in the sub-polar North Atlantic or North Pacific Oceans as the groundwork for follow-on process studies (Table 1). Pilot Southern Ocean time-series will be established toward the middle/end of OCCC Phase 1 as a prelude to a major Southern Ocean process study during Phase 2. Specific recommendations include:

- Continue support for the two current U.S. open-ocean time series stations at Bermuda (BATS) and Hawaii (HOT) and the repeat carbon survey of the equatorial Pacific (EqPac) and augmentation, where needed, of autonomous platforms and instruments to the ship based programs. 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 and/or establishment of new autonomous time-series stations in critical, high-latitude regions of the North Atlantic and North Pacific. 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 research ships from Canada regularly service this station, 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.

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.

- Extending the existing set of time-series stations into the Southern Ocean (section 7), 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).

5.4 North American Coastal Observing Network

The continental margins of the United States, Canada and Mexico are particularly important for two parallel and complementary research programs within the U.S. GCRP: Ocean Carbon and Climate Change (OCCC) and the North American Carbon Program (NACP). Although the area of the coastal oceans is relatively small, they are the active interface between the terrestrial 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 for ocean margin studies within both the OCCC and NACP are: improved estimates of air-sea fluxes of CO_2, carbon burial and carbon export to the open ocean; elucidation of factors controlling the efficiency of the solubility and biological pumps in coastal environments; quantification of the influence of margin biogeochemical processes on the chemical composition of open ocean waters; and quantification of the influence of river and groundwater inputs on margin biogeochemical processes. 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 where 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). Similar CO_2 drawdowns may occur 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 South- and Mid-Atlantic

Bight (Fig. 4). 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 upwelling of CO_2 and nutrient-rich waters can be observed in the coastal areas of California, in Monterey Bay and near Cape Hatteras among others. These upwelling systems are susceptible to large-scale oscillations (i.e., ENSO, PDO, NAO, etc.) in the climate system and, consequently, can be enhanced or shut down depending on the phasing of the climate variations.

Table 3. Variability of CO_2 Distributions and Fluxes in U.S. Coastal Waters from Regional Surveys and Moored Measurements

Location	Surface Seawater pCO_2 (μatm)	Instantaneous CO_2 Flux ($mol/m^2/yr$)	Annual Average ($mol/m^2/yr$)	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 meas.	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 meas.	Friederich et al. (2002)
Oregon Coast	250 - 640	ND	ND	Regional survey	van Geen et al. (2000)
Bering Sea Shelf in spring (Apr. - June)	130 - 400	-8 to -12	-8	Regional survey	Codispoti et al. (1986)
South Atlantic Bight	300-1200	ND	2.5	Regional survey	Cai et al. (2003)
Miss. River Plume (summer)	80-800	ND	ND	Regional survey	Cai et al. (2003)
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

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 North American 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, long-term coastal productivity as high as is observed in the Bering Sea is 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 at present to be able to constrain these estimates much further.

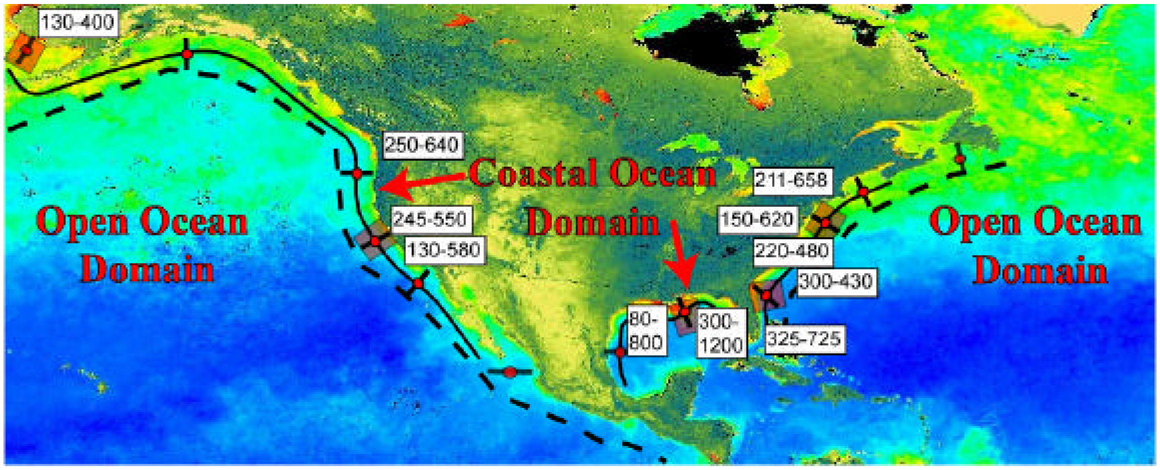

Figure 4: Range of pCO_2 values from selected coastal regions in North America. The sources for these data are given in Table 3 above. The recommended coastal time series and survey locations are also shown in the map.

Recommendations

The basic strategy for the North American coastal observing network is laid out as follows:

- Implement a backbone network of about 6-12 sampling sites (Fig. 4) 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. The moored platforms should also be utilized to make marine boundary layer atmospheric measurements, to complement the NACP aircraft profile and tall tower data, and relevant biogeochemical measurements in the water column to help interpret the observed variations in CO_2 flux.

- 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 but also information on carbon related parameters that cannot be derived from existing satellite systems, e.g., pulse and probe fluorometry.

- Carry out a series of intensive process studies at a subset of the long-term monitoring sites to evaluate the regional ecosystem structure and biogeochemical processes controlling continental margin carbon dynamics (described in Section 6.3). These process studies can also be used to help design optimum sampling strategies for the long-term observing network, constrain the necessary in situ measurement accuracies required to quantify the seasonal and interannual variability, and help evaluate remote sensing algorithm performance.

The continental margins are areas of strong overlap between the OCCC and the NACP (Denning et al., 2004), and the proposed coastal ocean implementation strategy has been developed in parallel. Overall, the effort will include: (1) long-term observations using coastal transects and buoys with autonomous sensors (outlined here); and (2) intensive process studies of the controls on the cycling and sources and sinks of carbon and other bioactive compounds (Section 6.3). It is anticipated that the OCCC implementation will focus primarily, but not exclusively, on continental shelf processes and shelf-open ocean connections. The NACP will focus primarily, but not exclusively, on continental shelf fluxes and land-shelf connections. The long-term observations will be coordinated between the two programs to provide a comprehensive assessment of the ocean margins and will be closely linked to the intensive process studies as well as related atmospheric and terrestrial elements of the NACP.

Given the complexity and variability of the coastal ocean and estuarine systems, it is important to develop a customized sampling plan that adequately addresses the regional conditions and leverages coastal projects that currently exist or are being planned by various agencies (e.g., NASA's coastal program; Oceans.US). The proposed number of OCCC coastal time-series (6-12) is based in part on the need to deploy a significant number of dedicated, ocean carbon moorings. An alternative approach that is also under investigation would involve adding biogeochemical sensors on existing buoys, leading to a substantial increase in the number of sites and spatial coverage. As an example, NOAA, through the National Weather Service and National Data Buoy Center (NDBC http://www.ndbc.noaa.gov), maintains and provides real-time meteorological and surface ocean data from ~80 moored buoy stations in the Atlantic, Pacific, the Gulf of Mexico, and the Great Lakes, the majority in coastal environments (Figure 5).

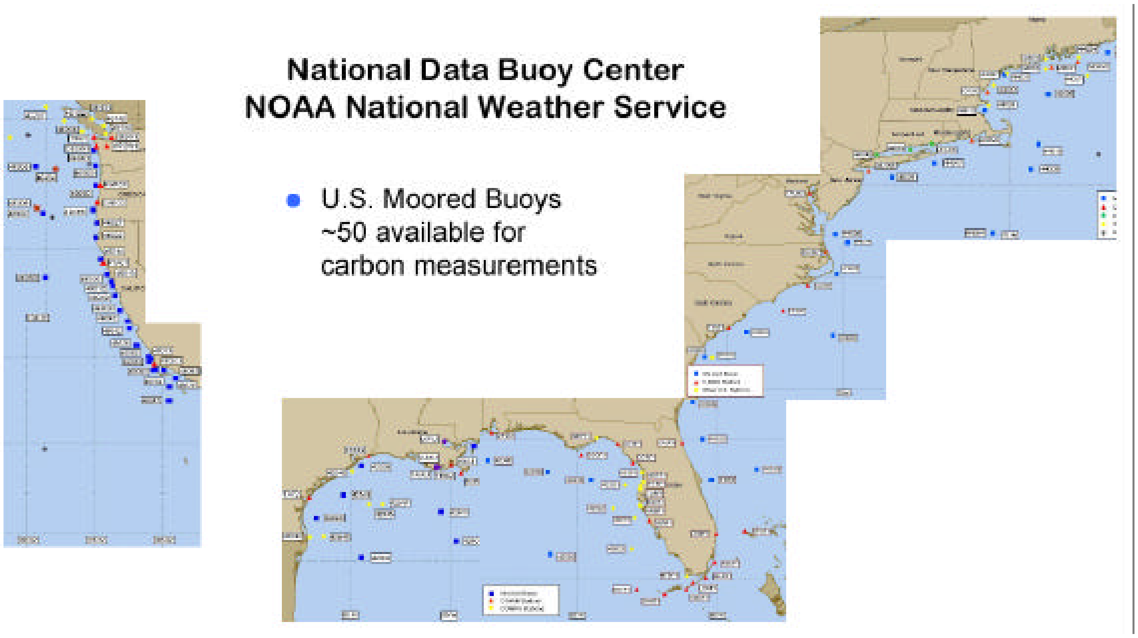

Figure 5: Map of National Data Buoy Center moored buoys along the North American continental margin with real-time weather observations. Approximately 50 buoys, marked in blue, are potential available for instrumentation with autonomous carbon system sensors.

The sampling plan must also consider related large-scale terrestrial and atmospheric programs. In particular, it would be advantageous for the coastal time-series moorings and cross-shelf transects to be co-located and/or coordinated with the coastal NACP atmospheric sampling network (e.g., surface measurements, tall towers, aircraft profiles and transects) to help interpret the atmospheric signals obtained from these locations. The ocean measurement suite for the time-series moorings should include air-sea partial pressure differences for CO_2 and O_2 for flux estimates. Technology development is required for automated, mooring deployable systems capable of delivering continuous atmospheric CO_2 and CO concentration data with an accuracy and precision sufficient for atmospheric needs. A similar suite of continuous underway surface water and atmospheric measurements, along with additional tracer measurements (e.g., C isotopes, SF6) should be included on the ship-based transects. Co-location of the cross-shelf transects with NACP terrestrial and riverine studies also will provide better constraints on the ultimate fate of river borne products. Sediment transport and resuspension studies also should be incorporated into the coastal ocean observing network, wherever possible.

The implementation strategies laid out here and for NACP only provide guidelines for the development of an observational program. The specific details of the implementation must be worked out with a planning workshop in the very near future (early 2004) that draws from the combined experience of the larger coastal oceanographic community.

Given the complexity of the coastal systems and the limited funding, the coastal observing system may need to be phased in over time. The scientific community must work together with program managers and the OCCC and NACP steering committees to optimize the available resources and maximize benefits through regular meetings (possibly every 2 years) of the PIs to discuss implementation successes and failures in addition to scientific results.

5.5 Remote Sensing

Satellite measurements will have a major role in OCCC because of their global and synoptic temporal and spatial coverage. Satellite data are well suited for estimating scales of variability of physical and biological 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., 2002a; 2002b), and for estimating global primary production variability (Behrenfeld et al., 2001). Global data sets of chlorophyll *a*, primary production, calcite, fluorescence line height, chromophoric dissolved organic matter (CDOM) absorption, photosynthetic available radiation (PAR), and sea surface temperature (SST), winds (vector and scalar), and sea surface height are generated operationally. Other relevant products such as particulate organic carbon (POC) concentration are being evaluated. Aircraft data, specifically the Airborne Oceanographic Lidar, have also been used extensively for regional surveys in support of JGOFS and iron fertilization experiments and for product validation (Hoge et al., 2003). Additionally, aircraft observations of other parameters (e.g., photosynthetic efficiency using a pump and probe lidar) are available that are not possible from satellites at this time.

In addition to ocean color remote sensing, satellite measurements of surface winds and SST, and, potentially, sea surface salinity (SSS) are used for CO_2 flux estimation. Wind speeds are required for most gas transfer function formulations, and CO_2 solubility is a function of SST and SSS (a proxy for alkalinity). Satellite surface wind measurements are derived from both active scatterometry (e.g., SeaWinds) and passive microwave radiometers (e.g., SSM/I) (e.g., Carr et al., 2002), and these observations are expected to continue indefinitely though likely in a more operational mode. It is hoped that the Aquarius mission, if given final NASA approval, or planned or European Soil Moisture and Ocean Salinity Mission (SMOS) will provide salinity data with sufficient accuracy to further improve estimates of pCO_2. Strategies have been developed to obtain global flux coverage on seasonal time scales through a combination of in situ observations, satellite measurements, data assimilation, and modeling. Finally, sea level data from satellite altimetry missions for certain areas such as the equatorial Pacific can be used to infer thermocline depth, integrated heat content, and new production (Turk et al., 2001).

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, depending on spatial variability scales, and the observational platform, e.g., dedicated cruise, research ship of opportunity, VOS, mooring, drifter, etc. Not all satellite measurements are of adequate resolution for coastal observations. For example, satellite salinity measurements at the 100 km scale resolution would not be useful for the coastal program.

In 2000 and 2001, NASA sponsored a series of workshops to help define future agency carbon cycle research priorities, measurement requirements, and technology development needs based on the science objectives outlined in Sarmiento and Wofsy (1999). The plan emphasized interagency collaborations, especially in field studies where key in situ measurements in support of algorithm development, calibration, and validation could be made during routine surveys (e.g., repeat hydrography and coastal cruises) and process studies cruises, and at time series sites. Most of the recommendations from these workshops (McClain et al., 2002a) were incorporated into the NASA carbon cycle and ecosystems roadmap, which identifies the agency's activities and deliverables over the next ten years. Importantly, the roadmap is also consistent with the Climate Change Research Program carbon cycle plan (Mahoney, 2003), for example with an emphasis on the North American Carbon Program (NACP; Wofsy and Harriss, 2002) in the near term with support for work in the Southern Ocean later in this decade. The roadmap also includes future missions to augment the Visible/Infrared Imager/Radiometer Suite (VIIRS), and to measure new parameters such as profiles of ocean particles from which can be inferred mixed layer depth. These new measurements would be competed under solicitations such as the NASA Earth System Science Pathfinder (ESSP) program; previous ESSP selections include the Orbiting Carbon Observatory for measuring column average atmospheric CO_2 (http://oco.jpl.nasa.gov/) and Aquarius for measuring ocean surface salinity (http://essp.gsfc.nasa.gov/aquarius/). Plans are now underway for the transition of satellite ocean color measurements from NASA research projects (e.g., SeaWiFS and the Moderate Resolution Imaging Spectroradiometer, MODIS; http://modis.gsfc.nasa.gov/) to a fully operational program under a tri-agency (DoC, DoD, NASA) Integrated Program Office. The National Polar-orbiting Operational Environmental Satellite System (NPOESS; http://www.ipo.noaa.gov/index.html) measurement suite also includes winds, SST, and sea level. The NPOESS strategy will facilitate an interagency approach to ocean carbon remote sensing and associated field measurement activities. The transition over the NPOESS Preparatory Project (NPP; http://jointmission.gsfc.nasa.gov/) will include calibration and validation functions, which must be extensive in order to meet scientific accuracy requirements.

Remote Sensing Contributions to Process and Time Series Studies

As noted above, satellite observations provide global coverage on a routine basis at a sufficiently high spatial and temporal resolution to observe a variety of important physical and biogeochemical processes and the linkages between them, especially when different satellite observations (ocean color, SST, surface winds, sea surface height) are combined with in situ data in an analysis (Murtugudde et al., 1999; Chavez et al., 1999). This approach is particularly necessary when investigating basin-scale processes and in cases where remote forcing plays a major role in modulating local processes. In support of field programs, the satellite and aircraft coverage provides a spatial and temporal context for in situ observations from cruises and time series stations. Such context is particularly important at sites such as BATS (Glover et al., 2002), where large-scale eddies play a major role in the biogeochemistry, and in other areas with large spatial gradients.

Remote sensing data can be invaluable for optimizing cruise plans and sampling strategies in near-real time (Yoder et al., 1994). Prior to near-real time support, field campaigns often missed major events that could have been surveyed had the information been available (McClain et al., 1986). Also, in some situations, the particular feature being sampled can either be too large or persist too long to be adequately described by the survey (McClain et al., 1984; Boyd and Law, 2001). But remote sensing coverage can provide the extended observations on the subsequent evolution of the event. Also, in the past, remote sensing data revealed events and processes that were totally unexpected, resulting in a reorientation of the process study objectives and approach. To avoid missed opportunities and help optimize cruise plans, the SeaWiFS and SIMBIOS (Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies; http://simbios.gsfc.nasa.gov/) Projects have provided near-real time data to nearly 400 field experiments since 1997, a statistic that underscores the community's recognition that remote sensing data is an integral part of field programs.

Remote sensing data can also be used in modeling studies beyond simply comparing spatial distributions and magnitudes of quantities such as chlorophyll with model outputs for model validation. In study areas with mooring array current measurements, for instance, the field data can be combined with time sequences of satellite data to estimate the magnitudes of the mass budget terms for biological properties such as chlorophyll or phytoplankton biomass, e.g., temporal rate of change, and horizontal advective and diffusive fluxes (McClain et al., 1990), which can then be compared to numerical model estimates of fluxes. The data can also be assimilated into numerical models (Friedrichs, 2002) to optimize model parameter values, e.g., growth, mortality and grazing rates, resulting in more accurate simulations and improved process understanding

Recommendations

Continue algorithm development, validation, and analysis of ocean color and related remotely sensed bio-optical properties. Much effort has been invested in the baseline ocean color products, e.g., water-leaving radiances and chlorophyll-a (Hooker and McClain, 2000), and these have been validated to a large degree. Most remaining problems with the water-leaving radiances result from deficiencies in the atmospheric corrections, especially with absorbing aerosols. Also, in the some regions of the Southern Ocean the operational chlorophyll-a algorithms may be off by as much as a factor of two. While primary production and particulate inorganic carbon are already MODIS products, more extensive validation and algorithm refinements are needed (McClain et al., 2002b). Other key ocean color products in Table 4, e.g., particulate organic carbon (POC) and dissolved organic carbon (DOC), will need substantial algorithm development and validation efforts. As the NASA carbon cycle and ecosystems roadmap evolves, algorithm development and validation efforts will be needed to meet the changing measurement requirements.

Table 4. Remote sensing observations relevant to ocean carbon dynamics.

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 Shipboard laser	Developmental Developmental	Global (Regional) Local
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 spatial sampling

! Regional: algorithm must be developed for specific biogeochemical provinces.

Additional acronyms

CDOM	colored dissolved organic matter
ESSP	Earth System Science Pathfinder

JGOFS	Joint Global Ocean Flux Study (
PAR	photosynthetically available radiation
POC	particulate organic matter
SSM/I	Special Sensor Microwave/Imager
SSS	sea surface salinity

Expand the in situ network of sensor calibration sites. SeaWiFS and MODIS use the Marine Optical Buoy off Lanai, Hawaii as their primary vicarious calibration site. A strategy with a single low latitude site has limitations, particularly for MODIS that does not tilt to reduce sun glint contamination. VIIRS (NPP and NPOESS) will not tilt either. New approaches to the on-orbit calibration need to be developed. A small network of relatively inexpensive calibration buoys and/or instrumented platforms is feasible given the improvements in instrumentation and measurement protocols over the past decade.

Continue support of community-wide technical enabling activities. Much of the success of the SeaWiFS program in providing high quality derived products was a result of calibration round robin, measurement protocol development, community bio-optical database, and in situ instrument development and evaluation activities. These activities have been primarily supported by the SeaWiFS and SIMBIOS Projects, which are ending in 2003. These enabling activities need to be continued, especially as the product suite is expanded and more emphasis is placed on coastal measurements.

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-sea CO_2 partial pressure difference (ΔpCO_2), sea surface temperature (SST; for solubility), and a gas transfer velocity (a function of surface turbulence, wind speed). An alternative approach under investigation bases the gas transfer formulation on radar backscatter rather than wind speed (Glover et al., 2001). The development of a robust remote sensing air-sea CO_2 flux parameterization will require a combination of coordinated mechanistic laboratory/wave tank and field process studies (see also Section 6.4), multi-sensor/multi-platform satellite data analysis, retrospective analysis of in situ data, and dedicated field validation efforts.

6 Process and Mechanistic Studies

While our understanding of the oceanic carbon system 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 even 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 OCCC, 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 concurrent and historical remote sensing data sets. 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. Therefore, the OCCC process-study model will be to conduct integrated process studies at time-series sites that operate for 5-years or more in order to characterize the seasonal to interannual variability for the site and set the process studies in the appropriate context (Section 5.3).

6.1 Upper Water Column and Mesopelagic Dynamics

The distribution and storage capacity of inorganic carbon in the ocean is governed to a significant degree by the biological transformations and fluxes within the upper water column and mesopelagic ocean. The biogeochemical dynamics of these two regions are closely intertwined; on relatively short time-scales, the upper ocean drives the biogeochemistry of the mesopleagic zone via the export of organic matter and particulate inorganic material, while on longer time-scales temporal evolution of the stocks of nutrients and inorganic carbon in the thermocline will modulate the rates and patterns of upper ocean production. The climate sensitivity of upper water column and mesopelagic dynamics can be framed in terms of the efficiency of the “biological pump” (Volk and Hoffert, 1985), which defined broadly is the partitioning of carbon in the ocean and atmosphere system relative to some theoretical maximum ocean carbon storage capacity. Biogeochemical factors that enhance ocean carbon storage include increasing oceanic nutrient inventories, the extent of surface nutrient utilization, the carbon to nutrient elemental stochiometry of export material, the organic carbon to calcium carbonate rain ratio, the regeneration length scale for sinking organic matter, and the fraction of sinking organic matter transiting the mesopelagic and reaching the deep-ocean.

Over the course of OCCC, open-ocean 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). Ideally, upper-ocean and mesopelagic process studies should be coordinated wherever possible. Although the current critical research needs for the upper ocean and mesopelagic regions differ somewhat, reflecting in part the greatly improved understanding on upper ocean processes over the JGOFS era (e.g., Fasham et al., 2001; Fasham, 2003), the discussion of the two are usefully combined here in terms of OCCC process studies because of commonalities in some of the underlying scientific questions, techniques and implementation strategies.

Rationale-Upper Water Column

The ocean surface layer (0-100 m) is a pivotal region for the marine carbon system because it is the site of the majority of the biological transformations of dissolved inorganic carbon into particulate material and because it is in direct contact with both the atmosphere and land margin. Biogeochemical processes in the upper water column drive the oceanic biological pump through the net formation and subsequent export of dissolved organic matter and particulate organic and inorganic matter via advection and gravitational sinking. The resulting vertical separation of organic and inorganic matter production from remineralization leads to the net transport and sequestration of carbon in the thermocline and deep ocean.

A diverse suite of biological factors, chemical conditions and ocean physics influences the magnitude and character of the export flux from the surface ocean which in turn impacts the efficiency of the biological pump and the ocean/atmosphere carbon partition. Michaels and Silver (1988) and Peinert et al. (1989) hypothesized that ecosystem community structure and its associated processes play an important role in modulating export and biological pump efficiency through alterations in surface and subsurface recycling rates, the relative contributions of dissolved versus particulate organic matter formation, the formation of bioinorganic ballast (e.g., siliceous and calcareous shells), and the size, sinking rates, and composition of particulate matter. However, the mechanisms governing ecosystem structure 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, biogeographical regimes that experience localized coastal or mesoscale upwelling or large-scale seasonal deep convective overturning followed by stratification and large nutrient entrainment generally support larger phytoplankton species (diatoms, haptophytes) and grazers compared to thermally stratified systems dominated by picoplankton. A change from a system dominated by small cells and small export fluxes to one dominated by large cells and large export fluxes may have no direct impact on the partitioning of carbon between the atmosphere and the ocean if other parameters (e.g., elemental stochiometry and nutrient utilization efficiency) are held constant. However, such a shift in ecosystem structure likely also induces changes in regeneration length scale that has significant secondary feedbacks on the depth distribution of carbon in the ocean. Because of this complexity in the ocean carbon system, we need comprehensive process studies that examine feedbacks as well as direct effects in determining sensitivity of the biological pump to climate change.

As the underlying ocean physical and chemical parameters respond to climate change over the next several centuries, there is the potential for large-scale shifts in marine 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 (Boyd and Doney, 2002; 2003).

Identified Research Needs-Upper Water Column

Biological pump efficiency: The development of a mechanistic understanding of the biological pump and it sensitivity to climate change may be achieved by 1) dramatically advancing our knowledge of biogeochemical fluxes in the oceans (which inherently give insights into processes) by making extensive observations of active processes and passive tracers (concentrations and isotopes) that constrain carbon and nutrient transfers, 2) identifying environmental factors that control the variability in plankton community structure and the magnitude of pelagic primary productivity and export, 3) 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 4) 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 autotroph growth is limited by nutrient availability, mostly as fixed inorganic nitrogen, phosphorus, or iron, and that carbon cycles within an ecosystem are tightly coupled to the cycle of other bio-elements through closely constrained elemental stoichiometries or Redfield ratios. For example, carbon cycling is often derived by scaling nitrogen fluxes by a factor of 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 supported by the supply of "new" nutrients from vertical and horizontal transport, atmospheric deposition and, in some cases, nitrogen fixation. However, in this scenario the capacity of the biological pump for carbon sequestration over longer time-scales is restricted because of the coupling of carbon and nutrients. As organic matter is remineralized at depth, it not only generates nutrients that can fuel marine new 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 upper ocean mechanisms including changes in the: 1) availability of limiting nutrients due to changes in fluvial and aeolian transport of iron, phosphate and fixed forms of nitrogen, which could lead to a transient increase of carbon sequestration from the upper marine layer through biological activity and long-term changes in ocean nutrient inventories; 2) magnitude of nitrogen fixation relative to denitrification, which can also increase or decrease the ocean inventory of available nitrogen; 3) surface utilization efficiency of limiting nutrients, particularly in areas such as the HNLC regions of the Southern Ocean, Equatorial and North Pacific with non-zero levels of unused macronutrients; and 4) the C:N:P:Fe stoichiometry in key food web components, which can change the amount of carbon deep-ocean sequestration (and not incidentally alter significantly biogeochemical cycles at the ecosystem level, e.g., Sambrotto et al., 1993; 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 transport carbon from the surface to the deep ocean, their net effect on 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 produced 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. Finally, growing evidence suggests a linkage between the vertical remineralization length-scales of organic matter and the sinking fluxes of hard tissue ($CaCO_3$, biogenic silica) (e.g., Armstrong et al., 2002).

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. The ocean is inherently turbulent and heterogeneous, with variability on many temporal and spatial scales. The scaling up of local process information and in-situ observations to ocean basins and the globe remains a major challenge (e.g., using VOS ship tracks and moorings to constrain seasonal and basin-scale CO_2 air-sea flux estimates). A good example of the potential difficulties is the on-going debate about the degree to which the upper ocean is net heterotrophic versus net autotrophic. The traditional paradigm is that the upper ocean should be a region of net organic carbon and oxygen production, but shipboard measurements in the subtropics have been used to argue for exactly the reverse (e.g., del Giorgio et al., 1997; Duarte and Agusti, 1998). Recent work by Karl et al. (2003) using mooring data suggests that the resolution to the problem may result from better sampling of high frequency variability. They observe brief periods of intense autotrophy over a background of weak heterotrophic conditions, which when integrated in time lead to net autotrophy. This highlights the need to probe and understand the ocean at the time/space scales relevant to the underlying mechanisms not just the large-scale responses.

Changes in climate may involve changes in the baseline conditions (i.e., increased sea surface temperature and water column stratification or shifts 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, El Nino-Southern Oscillation and Pacific Decadal

Oscillation 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 also depends upon 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 (e.g., Carlson et al., 1994; Ducklow et al., 1995). Annual global export of dissolved organic carbon (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. Because most DOC is remineralized in the thermocline, system dominated by DOC export lead to carbon sequestration of a few years to decades at most; by contrast POC export to the deep ocean leads to enhanced ocean carbon storage on centennial time-scales or longer, However, little is known about the factors regulating the partitioning of exported carbon between dissolved and particulate form, 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 particulate organic carbon (POC) and DOC, its regional variability, and its sensitivity to changes in environmental conditions.

Rationale-Mesopelagic Processes

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. 6), 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 significant feedback to climate change.

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 indicate 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, IMBER, etc.).

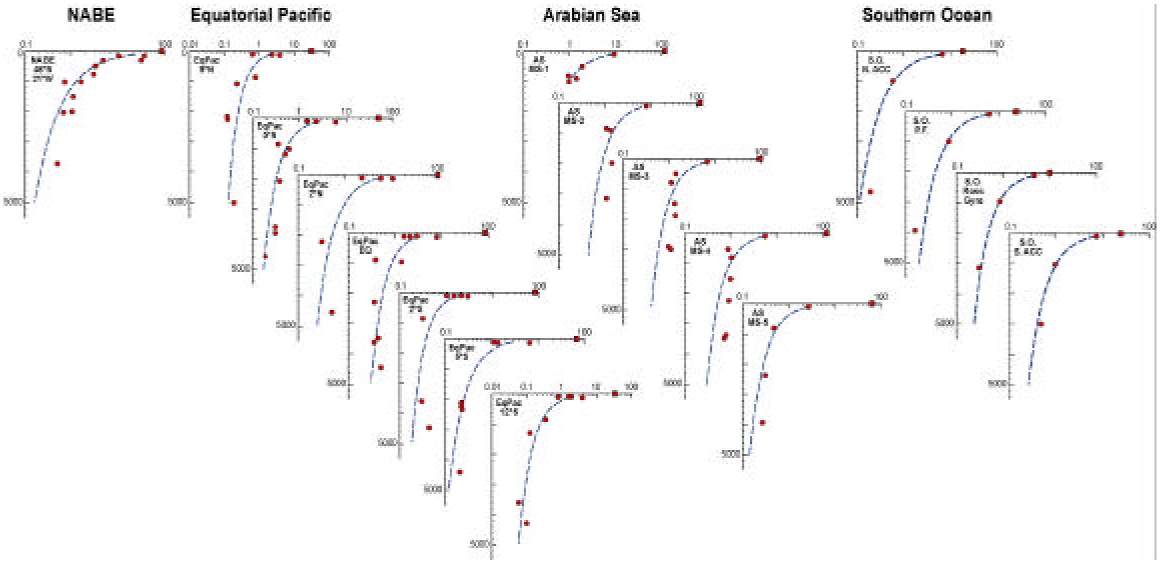

Figure 6: Vertical particulate organic carbon flux versus depth from sediment traps at 17 stations conducted as part of the U.S. JGOFS regional studies (Berelson, 2001). The surface red square in each subplot represents the annual primary production integrated over the euphotic zone. Note the logarithmic scale for thee vertical fluxes.

The depth scale for remineralization of particulate organic and inorganic 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. Alternatively, zooplankton can increase the sinking rate of POC by repackaging suspended material into rapidly sinking 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

Zooplankton grazing may also serve as a significant remineralization pathway for $CaCO_3$ in the mesopelagic zone. Coccolithophores are recorded among stomach contents of copepods because their calcareous scales resist digestion. Harris (1994), however, found that less than 50% of the ingested calcite of coccolithophores could be found in the copepod fecal pellets, suggesting that the calcite had been subjected to acid digestion in the zooplankton gut.

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 to better predict C flux at any given depth (Armstrong et al. 2002).

The mesopelagic ocean is also characterized by large vertical gradients in dissolved organic matter (DOM), which 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 and carbon storage in the ocean interior (e.g., Hansell and Carlson, 1998; 2001).

Identified Research Needs-Mesopelagic

Regeneration length scales. Empirical power-law fits to a composite of shallow floating sediment trap data (Fig. 6; 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 determines 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 in the mesopelagic 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. Mass budgets must take in to account the lateral convergence of organic matter via advective DOM transport as well as active biological vertical transport by, for example, zooplankton migration. 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.

Recommendations

Mid-sized process studies linked to existing, open-ocean time-series stations: Individual and mid-size projects on upper water column and mesopelagic dynamics should be initiated early in Phase 1 of OCCC at existing open-ocean time-series sites in the North Atlantic and North and Equatorial Pacific (e.g., HOT, BATS; Section 5.3). The process studies will target issues of climate feedbacks and sensitivity of the ocean carbon system as described above but will also provide a venue for exploratory research and methods/technology development. Modeling and remote sensing studies will be incorporated as integral component of the process studies. The individual and mid-sized projects during the initiation period of OCCC will take advantage of the considerable community planning that has already occurred, will help address outstanding scientific questions raised by existing data records (thus increasing the value of the historical time-series data sets), and lay the ground-work for integrated process study/time series projects in other oceanographic regimes.

Physical oceanographic context for time-series: Integration of a more robust physical oceanographic component to ocean carbon process studies is required to resolve issues such as mass balance for carbon and relevant biogeochemical species and the impact of high frequency forcing (e.g., mesoscale eddy pumping) on marine ecosystems and carbon cycling. To initiate this, we recommend that projects be conducted to better characterize the submesoscale and mesoscale physical circulation environment surrounding one or both of the open-ocean U.S. time-series sites (HOT and BATS) to allow a 4-dimensional study of the physical and biogeochemical processes. One approach might involve using an array of moorings to quantify the flow field. Such experiments will help determine future requirements for new time-series sites. We currently do not have sufficient information, in many cases, to predict how much and on what scale physical knowledge is required to make major advances in understanding the carbon cycle. These experiments should take advantage of existing moorings and planned NSF (e.g., ORION) and NOAA activities.

Integrated Northern Hemisphere process studies: A large-scale, open-ocean process study should be conducted in the Northern Hemisphere over the second part of OCCC Phase 1. The underlying framework of the study, which may be structured as a federation of mid-sized projects, will be to utilize natural climate variability (e.g., North Atlantic Oscillation, Pacific Decadal Oscillation, El Nino-Southern Oscillation) as probes for the mechanisms of ocean carbon system response and climate sensitivity. A key rationale is that climate variability, anthropogenic climate change, and marine ecosystem and biogeochemical responses and feedbacks all occur on regional scales, order of 1000's of kilometers and years, rather than local or global scales. The field effort, therefore, will require a more spatially and temporally extensive approach than historical campaign style oceanography and will likely involve contemporaneous comparative studies of the climate variability response of different biogeographic regimes (e.g., subpolar versus subtropical gyres; North Atlantic spring bloom versus North Pacific HNLC). This will only be possible if the process study builds closely upon observing system elements (Section 5) for the Northern Hemisphere integrated through numerical modeling and data assimilation (Section 8). As outlined in the OCCC Phase 1 Timeline (Figure 1), the sequence of events is as follows:

1) Deployment of new time-series mooring(s) early in Phase 1 in subpolar or equatorial locations to define patterns of variability that will be used to probe the response of the ocean carbon system to climate change;

2) Designing a comprehensive process study to determine the climate sensitivity of the ecosystem structure and of individual components of the ocean carbon system, both in the surface ocean and in the mesopelagic zone; and

3) Maintaining time series following the process study with the overall goal of combining in situ data obtained from the time-series with data available from remote sensing together with modeling in an integrated effort that will continue to explore the climate sensitivity of the ocean carbon system in the study region(s).

Open planning workshops should be held early in OCCC Phase 1, in conjunction with the citing of the new time-series, to refine a detailed implementation plan.

Technologies and approaches: The large range of temporal scales of perturbation and response of marine pelagic ecosystems require that the OCCC process studies be based on multi-disciplinary and multi-platform approaches exploiting new technological developments in order to address the mechanistic questions detailed above. In addition to ship-based sampling and observation, OCCC process studies should, therefore, take advantage of improved physical, chemical and biological analytical methods (Section 9.1), new autonomous sensors and deployment platforms (Section 9.2), and operational and emerging satellite remote sensing capabilities (Sections 5.5 and 9.3). Laboratory-based process work, controlled mesocosm studies, and in situ experimental manipulation or perturbation studies (e.g., mesoscale iron enrichment) are also required. Continued technological development is clearly needed (Section 9), and the time-series programs will provide the opportunity for the refinement, integration and implementation. Specifically, targeted research is need on 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. The temporal perspective of historical remote sensing data for the study sites, together with the spatial context provided by concurrent measurements from the existing suite of sea-viewing sensors, is key to an optimal interpretation of field measurements. We recommend that concurrent remote sensing studies be explicit in process studies.

Study sites: Existing and historical programs such as JGOFS, GLOBEC (Global Ocean Ecosystem Dynamics; http://www.pml.ac.uk/globec/main.htm), CalCOFI (California Cooperative Oceanic fisheries Investigations; http://www-mlrg.ucsd.edu/calcofi.html), LTER (Long Term Ecological Research; http://lternet.edu), and LMER (Land Margin Ecosystem Research) provide 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. At a minimum we recommend an end-member approach, covering at least an oligotrophic gyre, high latitude, equatorial, and coastal upwelling 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 several years of OCCC Phase 1. 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 historical context and ongoing infrastructure in high latitudes affected by climatic changes associated with PDO and NAO respectively. The PAPA and MIKE experience should serve as starting points for discussions at planning workshops concerning the nature and location of OCCC subpolar process studies and time-series sites. We recommend that autonomous, biogeochemical sampling platforms be deployed in both the subpolar North Pacific and North Atlantic (see section 5) and that at least one of these time-series sites be chosen for the implementation of upper water column and mesopelagic process studies in OCCC Phase 1. 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 Phase 2 of the program.

- *Equatorial Pacific sites:* The spatial and temporal evolution of surface pCO2 in the Equatorial Pacific are well documented for the last decade based on biannual underway surveys and continuous moored CO2 system observations (http://www.pmel.noaa.gov/uwpco2/) conducted in conjunction with the TAO project (Tropical Atmosphere Ocean http://www.pmel.noaa.gov/tao/). These data combined with other historical data sets have been used to quantify and determine the mechanisms behind the large oscillations in net air-sea CO_2 flux associated with ENSO and provide the most detailed regional view of interannual variability of the ocean carbon system. The infrastructure of the TAO mooring array offers an ideal opportunity, and we recommend that an OCCC process study and more comprehensive biogeochemical time-series be developed for the Equatorial Pacific building off this capability.

- *Continental margin upwelling sites:* Detailed discussions of the role of ocean margins in the global carbon cycle can be found in Sections 5.4 and 6.2. 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 dynamics of carbon at a basin scale. As pointed in section 6.2, process studies in these regions should be implemented in a subset of the NACP network sites.

6.2 *Continental Margin Biogeochemistry*

Rationale

Many of the lessons learned from open ocean studies cannot be applied directly to ecosystems at ocean - continent boundaries. Among the characteristics that differentiate margins from open ocean systems are (see Figure 7): riverine and groundwater inputs of organic and inorganic nutrients and carbon, altered input ratios of nutrients, exchanges with bottom sediments, strong and direct anthropogenic impacts, high spatial and temporal variability, enhanced water column cross isopycnal mixing due to tides and friction with sea floor, focused and intense wind-driven upwelling, close coupling between benthic and pelagic ecosystems, lateral sediment transport and sediment resuspension that may be a source of micronutrients and ballast materials, elevated atmospheric inputs of dust and concentrated carbon sources associated with gas hydrates. Additionally, potential coastal sites for ocean CO_2 disposal must be evaluated for feasibility and possible environmental impacts.

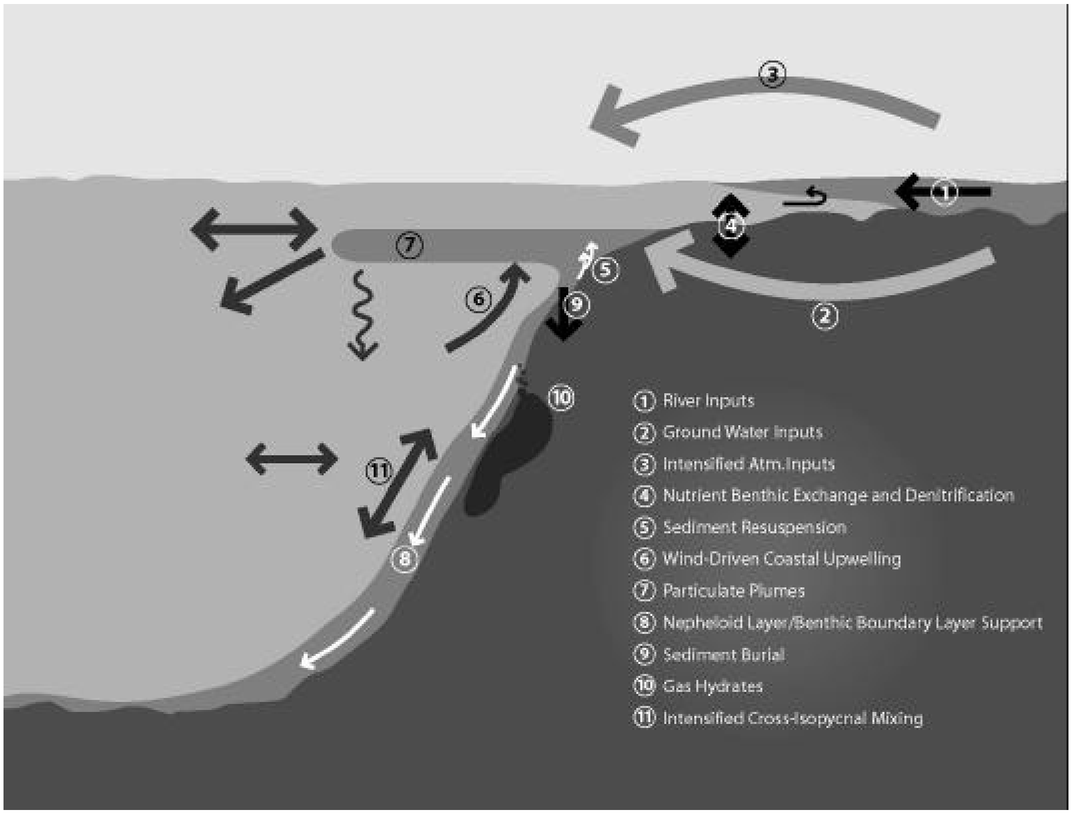

Figure 7. Schematic representation of processes that are either unique to or intensified at ocean - continental boundaries that may significantly impact ocean carbon distributions.

The impact of ocean boundary processes on the global carbon budget is not well known, but these processes may provide major pathways for transferring carbon between important, climatically relevant reservoirs. For example, riverine inputs and wind-driven, coastal upwelling support extremely high rates of primary biological production and organic carbon sedimentation relative to the open ocean. Sea floor and water column-based estimates of the particulate organic carbon flux suggest that perhaps as much as 1/2 of the total biological pump transfer of organic carbon to deep waters occurs adjacent to the continents (Jahnke, 1996; Schlitzer, 2000). Denitrification at margins is the dominant removal of biologically available nitrogen from the ocean and thereby exerts control on global marine production (Codispoti et al., 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 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 (Vlahos et al. 2002, Yool and Fasham, 2001). Importantly, at some locations, direct inputs of terrestrially derived carbon via rivers, groundwaters and tidal exchange with coastal waters may supply much of the carbon transported off the shelf (McKee, 2003). This implies that assessment of air-sea exchange may not be sufficient to fully quantify the oceanic CO_2 sink and that terrestrial and oceanic carbon pools may be tightly linked through coastal transport processes. Additional carbon uptake through high rates of biological productivity, which characterize river-ocean margins, further suggest that these systems may be important focal points for the sequestration of anthropogenic carbon.

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 atmospheric, terrestrial and internal 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. Studies of the coastal regions must balance the need to quantify critical carbon transfers while continuing to work toward a fundamental and mechanistic understanding of the carbon cycle.

Specific examples of important, poorly constrained fluxes, include: riverine and groundwater inputs, coastal air - sea exchange, sediment/water column exchange, resuspension and lateral sediment transport, shelf edge exchange processes such as interactions with oceanic boundary currents and eddies and exchange between surface and deep waters. 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 between 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, opal and $CaCO_3$, and anthropogenic affects may significantly uncouple the individual nutrient and carbon 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, due to shifts in precipitation patterns and runoff intensity, and changing upwelling rates, due to shifts in wind regimes and strengths. Biologically available nitrogen inputs from land have increased 2-5 times since the early 1900's (Seitzinger and Kroeze, 1998). Furthermore, significant amounts of particulate and dissolved organic and inorganic carbon from riverine fluxes represent carbon removed from the atmosphere via terrestrial fixation. Understanding the fate of this carbon in margin systems is critical to evaluating regional and continental scale net atmospheric exchange. Many of these exchanges will be altered through anthropogenic driven changes to climate, terrestrial ecosystems, and the coastal environment.

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 that will facilitate regional scale carbon studies include improved models tuned to specific coastal regimes, synoptic and higher resolution coverage with remote sensing, chemical sensor measurements and the implementation of a coastal ocean observing system. 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 significant anthropogenic inputs. Along North America, regions exhibiting these characteristics will naturally include broad and narrow continental shelves and regions that are predominantly CO_2 sources and CO_2 sinks. Examples of possible locations are: 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 pCO_2 monitoring 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-scale program. Furthermore, the continued expansion of coastal observing systems will provide a longer temporal context in which individual studies can be interpreted.

Transport Studies: Initial studies need to assign a high priority to establishing the overall distribution and transport of carbon at each location. Specific transfers studied should include open ocean-margin exchange, particulate burial and/or flux to deep waters, air-sea flux, sediment water exchange and lateral sediment transport, and river and groundwater fluxes. Some of these studies (e.g., river and groundwater fluxes) will be conducted in close collaboration with the NACP. 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. Promising technologies include moored, towed, and free floating instruments for developing high resolution measurements in the water column and at the sea surface. The observations should be developed in conjunction with regional and global modeling efforts that explicitly include the continental margins.

Process Measurements: Intensive coastal process studies should be conducted to better understand the ecosystem and carbon system 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 (Section 9). 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. However, because many of the linkages between hydrographic, biogeochemical and ecological processes have been hypothesized but not identified and constrained, detailed, shipboard 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 (within the water column, benthic boundary layer and seabed) 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, deposition, respiration, burial, 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 such as the NACP. Of particular importance in this context, will be the use of coastal observatory measurements (e.g., ORION) to identify short-term, episodic phenomena and long-term trends, both of which are mostly missed by shipboard observations. Additionally, detailed, shipboard studies will be limited to a few specific locations. Observatory-based measurements will permit broader spatial comparison and, over time, extrapolation of results to other margin settings, significantly improving our understanding of the role of ocean-continental boundary systems in the global carbon budget.

6.3 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 ? 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 CO_2 over the ocean, alleviating previous shortcomings as described 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) (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 infrared 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 recommendations are presented in order of priority.

Dedicated gas exchange process studies: The two recently completed NOAA efforts, the GasEx 1998 and 2001 studies, show the feasibility of the direct flux measurements and provide initial results on parameterizations with high frequency forcing. Future studies should have a greater focus on parameterization using remotely sensed products, cross-validation with independent flux techniques, and coordination with the intensive basin observations of pCO_2 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 CO_2 and other gases, employment of proxies such as mass balance approaches of radon, and deliberate tracers.

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 the large spar buoys proposed as part of the NSF ORION ocean observatory initiative. Precise and accurate continuous atmospheric CO_2 concentration measurements should also be included to tie back in with the atmospheric observing network. 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 CO_2 fluxes as well provided they fulfill the stringent measurement criteria necessary for direct CO_2 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.

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 research effort on air-sea gas exchange 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 O_2/N_2, $^{13}C/^{12}C$, and ^{13}C 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 affect 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 system 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 OCCC.

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 studies over the last decade. However, the sensitivity to climate change of important processes that control CO_2 transfers has yet to be investigated. In order to predict future concentrations of CO_2 in the atmosphere (Goal 4 of the CCSP; Sarmiento and Wofsy, 1999), 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 serve as a foundation for the next generation field program. Furthermore, future programs will benefit from technological developments (Section 9) that will permit continuous observations 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 OCCC, it is recommended that: 1) these synthesis activities be completed, 2) pilot studies be implemented, 3) new observational systems be developed, and 4) improvements be made to the models used to simulate the ocean carbon system. These activities will lay the groundwork for an intensive Southern Ocean field effort in Phase 2 of OCCC, designed specifically to determine the sensitivity to climate change of the physical and biogeochemical processes that regulate carbon fluxes in the Southern Ocean.

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 deepwater 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 (LeQuere et al., 2002). 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 determine 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, it is first necessary to characterize the time and space scales of interannual variability as well as the amplitude of the variability of key environmental parameters associated with these oscillations. Archived data from remote sensing and meteorology should be analyzed with a view toward characterizing the patterns and amplitudes of variability in those parameters believed to influence carbon fluxes in the Southern Ocean (e.g., wind speed, sea ice extent, sea surface temperature and heat content, etc.). Analysis of the growing body of in situ data, including results from process studies, repeat hydrography, and underway data from volunteer observing ships, should be coordinated with the analysis of remote sensing results to determine the response of the upper water column to surface changes detectable by satellites. Defining these scales of variability will provide a basis for designing future process studies that will exploit this natural variability to determine the sensitivity of carbon fluxes in the Southern Ocean to changing climate conditions.

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.

Pilot Studies: Concurrent with the synthesis of historical data, pilot studies offer a complementary approach to characterize the processes that regulate carbon fluxes in the Southern Ocean. Furthermore, pilot studies can be designed to improve the parameterization in ocean carbon models of the physical and biogeochemical processes that regulate carbon fluxes in the Southern Ocean. Whereas dedicated pilot studies may be planned solely under the auspices of OCCC, opportunities exist for synergistic collaboration with other programs.

Many of the processes that regulate carbon fluxes in the Southern Ocean, such as meridional overturning circulation, isopycnal and diapycnal mixing, and the air-sea exchange of heat, momentum, freshwater and dissolved gases, also play a critical role in the climate variability being investigated by CLIVAR. Studies designed to investigate these processes are already underway, or are in advanced stages of planning, within US CLIVAR. An early priority during Phase 1 of OCCC will be to explore the potential benefits of collaboration with US CLIVAR in studies of the Southern Ocean.

Process studies that are underway, or at advanced staged of execution include:

- AnSlope (Cross-slope exchanges at the Antarctic Slope Front) is studying deepwater formation near the continental margin of Antarctica, which drives the lower limb of meridional overturning circulation. Collaboration with AnSlope offers an opportunity to examine the processes that regulate the ventilation of the deepest water masses in the ocean. Cruises are already underway in the Ross Sea sector of the Southern Ocean.

- SAMFLOC (Subantarctic Mixed Layers and Overturning Circulation) will examine air-sea fluxes and cross-frontal transport involved in the upper limb of meridional overturning circulation. Field work is planned for the SW Pacific region of Antarctic Intermediate Water formation.

Process studies that are being developed or supported within US CLIVAR include:

- DIMES (Diapycnal and Isopycnal Mixing Experiment in the Southern ocean) involves a ballasted float study, microstructure measurements, and a tracer release experiment to determine diapycnal diffusivity and isopycnal mixing throughout a large sector of the Southern Ocean. The study is designed to improve our understanding of the role of these processes in meridional overturning circulation and simultaneously improve the parameterization of these processes in numerical models.

- GASEX-SO (a Southern Ocean air-sea CO_2 exchange study) is being developed under the auspices of US CLIVAR, although it is anticipated to have close ties to SOLAS and OCCC as well. The objective of GASEX-SO is to reduce the uncertainty in the air-sea gas transfer velocity at high wind speeds characteristic of the Southern Ocean.

- The development of profiling float capabilities in the seasonal sea-ice zone. Technological developments, especially the ability to transfer many stored profiles over the iridium system, along with sub-ice float positioning, will open up the seasonal sea-ice zone to routine, autonomous sampling.

In addition, OCCC should explore pilot studies that could be created jointly with CLIVAR. Both eddy interactions with mixed layers and sea-ice are key phenomena, which exert a strong control over climate and biogeochemical fluxes. For example, sea ice is an important variable affecting both climate and carbon fluxes. Sea ice influences the air-sea transfer of momentum, heat, freshwater, and gases. Sea ice also plays a crucial role in regulating the light field experienced by phytoplankton. When present, sea ice shades the mixed layer, creating light-limiting conditions for phytoplankton growing there. When sea ice melts, stabilization of the upper water column by the addition of fresh water may create favorable light conditions by reducing mixed layer depth. Early in Phase 1, a workshop should be held to explore the feasibility and desirability of a joint OCCC-CLIVAR pilot/process study of sea ice in the Southern Ocean.

Volunteering Observing Ships (VOS) and Technological Developments: The remote location and harsh operating conditions make it both difficult and expensive to conduct shipboard operations in the Southern Ocean. Consequently, acquisition of data from VOS and from in situ observational networks will necessarily play a large role in future Southern Ocean studies. Expanding the network of VOS (Section 5.2), as well as the parameters measured aboard these ships, will help characterize both the scales of variability in the Southern Ocean (see above) and the biogeochemical response to changes in environmental forcing. Development of new sensors and samplers for deployment on autonomous platforms (Section 9.1) will further contribute toward this goal. Some examples of activities that should be pursued aggressively during Phase 1 of OCCC are described below.

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 be expanded, as well. For example, pCO_2 systems could be installed aboard Coast Guard icebreakers, 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 database 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.

Expanding the VOS program to include additional parameters will help identify the processes that regulate pCO_2 at the surface, and the sensitivity of these processes to climate change. Relevant measurements include the concentrations of nutrients, dissolved oxygen, and dissolved inorganic carbon (DIC), together with the isotopic composition of DIC, oxygen, nitrate and silicic acid. The isotopic composition of dissolved bioreactive species can be used to constrain the processes responsible for the observed changes in the concentrations of these species. Concentrations of chlorophyll a, particulate organic carbon, and particulate inorganic carbon should be measured as well, both to establish the patterns of variability of these parameters and to determine their relationship to environmental conditions. These results will also contribute to the database used to develop and calibrate algorithms by which these parameters can be assessed by satellite remote sensing.

Transport within the Antarctic Circumpolar Current is closely related to the structure of isotherms in the upper water column, and these are known to exhibit substantial interannual variability. Equipping VOS with XBT (or XCTD) and hull ADCP measurements, together with state of the art meteorological measurements, will identify relationships between underway surface pCO_2 and relevant physical parameters. This information, in turn, will be exploited in the design of process studies to be conducted during Phase 2 of OCCC.

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 9.1). 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 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 also 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.

Many of the variables that influence carbon fluxes in the Southern Ocean also play a role in the transport of heat and freshwater. Consequently, model development in OCCC should be undertaken in collaboration with parallel efforts in CLIVAR. For example, OCCC and CLIVAR investigators can work together to improve model parameterizations of subgridscale processes, such as eddy mixing, convection, and downslope transport near Antarctica. The dynamics of sea ice, and their influence on air-sea fluxes, is another area of model improvement with common interests in OCCC and CLIVAR. An early priority will be to hold a workshop to define common modeling objectives in OCCC and CLIVAR, and to lay out a strategy to achieve those goals.

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 system 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 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 collection of field data specifically to address known model deficiencies. The overall OCCC 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 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 CO_2; “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 OCCC:

- 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 required in order to improve future climate projections and to develop a better fundamental understanding of the ocean carbon system 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 system 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 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 management centers (Section 10.1) and ocean carbon data assimilation systems. The ocean carbon data management 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) and merging of data products from different sources. 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 system 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. A number of data assimilation approaches have been followed in other disciplines. 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 system 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; 1999) 30-year climatology of surface pCO_2 measurements and the Wanninkhof (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 and Harriss, 2002; Denning et al., 2004), 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 under-sampling 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 (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 climatologies 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 (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 0.4 $PgCyr^{-1}$ less CO_2 entering the atmosphere from the eastern equatorial Pacific (Chavez et al., 1999, Le Quéré et al., 2000, Feely et al., 2002). Other significant sources of interannual ocean carbon variability include the North Atlantic Oscillation (NAO) and Antarctic Circumpolar Waves (Le Quéré et al., 2002). Errors in these variations, or assuming fluxes or patterns fixed in time, can lead to biases in the attribution of interannual carbon system 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 future 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 PgC yr^{-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 management centers to undertake or coordinate the compilation, quality control and distribution of in-situ and remote sensing data relevant to the ocean carbon system, as well as derived synthesis products (e.g., surface fluxes; assimilation fields) (Section 10.1);

- 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 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 system that is optimally consistent with all available data-hydrography, pCO_2 surveys, time-series, remote sensing, and floats/drifters-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 the 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 Methods and Technology Development

A key component of OCCC is an up front investment in the methods and technology development that will enhance our ability to characterize specific biogeochemical mechanisms and study the surface and subsurface structure of all interacting carbon components on key time and space scales. Emerging chemical and biological techniques, such as new isotopic and genomic analyses, allow us to discover new phenomenon and ask previously unasked questions about the marine environment. The continuous push to develop autonomous in-situ and remote measuring systems, in contrast, allows for orders of magnitude more observations than from traditional approaches and is driven by the need to simultaneously reduce ship time, expand temporal and spatial coverage, and collect data under adverse conditions. Some of these advances are available now, others are in development, and others are anticipated through continued research. This section focuses on ocean carbon system measurements; but to quantify, understand, model, and predict the CO_2 variability of the atmosphere-ocean system also requires complementary measurements of meteorological and physical oceanographic variables. OCCC will greatly benefit from physical data from related field programs (e.g., CLIVAR) and excellent real-time satellite and weather/climate prediction model products such as wind, irradiance, aerosols, biomass assessments, and ocean circulation.

9.1 Chemical and Biological Techniques

Improved shipboard and shore-based chemical and biological techniques now available or under development offer to dramatically advance marine biogeochemistry. Many of these techniques, however, require further testing and validation through dedicated laboratory experiments and in the water fieldwork. The existing and new OCCC open-ocean and coastal time-series stations (Section 5.3) and process studies (Section 6) provide ideal, integrated frameworks for such technology development studies. In turn, the resulting new measurement capabilities will greatly contribute to future OCCC process studies and the deployment of the full global ocean carbon observing network. The OCCC program, therefore, includes a focused, research element in the first part of Phase 1 on chemical and biological technique development including:

Sensors/analyzers for bioactive tracers: Recent years have seen dramatic advances in our ability to characterize chemical properties of the surface ocean (Section 9.2). There is still a great deal of opportunity for improving our ability to sample and analyze upper ocean waters and measure the distribution of properties that constrain bioactive fluxes in the oceans.

Continuous 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 (Section 9.2). 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.

Molecular approaches: 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 organic carbon is partitioned in the coastal and open upper ocean and the processes that control the efficiency of its use in the mesopelagic layer.

Environmental Genomics: New methods and technologies are frequently utilized to reexamine existing dogma. "Environmental genomics” is a rapidly expanding field of research that uses nucleic acid sequences from natural microbial ecosystems to investigate diversity, function and potential linkages to larger scale biogeochemical processes. In the late 1980's and early 1990's the use of molecular tools to study the ribosomal RNA (rRNA) sequences of uncultured microbes unveiled a vast diversity of prokaryotes in the ocean ecosystems (DeLong et al., 1989; Giovannoni et al. 1990). High throughput sequencing of environmental DNA is an emerging technology that will allow more of the assumptions in microbial ecology and the underlying mechanisms of biogeochemical processes to be reconsidered. For example, in one of the first applications of environmental genomics, Delong and colleagues sequenced a bacterial artificial chromosome (BAC) containing the SAR86 rDNA gene. Linked to this gene was a rhodopsin gene, which was later shown to be a light driven proton pump, an energy system previously unknown within the bacterial domain. If these organisms use rhodopsin for photoheterotrophy (i.e., a metabolic process in that gains energy from the sun and carbon from organic matter) then the presence of these organisms in the upper ocean has clear implications towards our understanding of how carbon is processed within the surface ocean. Molecular tools are also being used to study different facets of the nitrogen (Zehr et al. 2003) and sulfur cycle (Moran et al. 2003) in the ocean.

There are already numerous marine phytoplankton genomes that have been sequenced by the Department of Energy and are available to the scientific community including *Synechococcus*, *Synechocystis*, *Trichodesmium*, several strains of *Prochlorococcus*, and a diatom (*Thalassiosira pseudonana*). Numerous other important marine organisms will be sequenced in the coming years including the coccolithophore *E. huxleyii*, and the unicellular nitrogen fixer *Crocosphaera*.. In addition, The Institute for Biological Energy Alternatives, founded by Craig Venter, is currently working on a large-scale DNA sequencing project to determine much of the microbial diversity the Sargasso Sea, and potentially continuing with other surface water environments. Together this combination of whole genome sequencing of cultured microbes and environmental DNA will greatly expand both our knowledge of major marine phytoplankton and the diversity present in the natural environment.

The rapidly growing database of marine microbial DNA sequences allows the application of cutting edge technology from molecular biology such as DNA microarrays (Gibson 2002). The arrays consist of up to 10,000 unique DNA probes robotically spotted onto a small glass slide. Each of these probes can correspond to a gene from the genome of microbe, and the presence or absence of that gene in a sample, or the expression of that gene by microbes in the sample can be determined by hybrization of fluorescently environmental samples (DNA or RNA, respectively). The expression of functional genes, such as those involved in nitrogen fixation, carbon uptake, metal uptake, or other metabolic processes can then all be monitored simultaneously. Currently, several groups are developing whole or partial genome microarrays of marine organisms or environmental sequences for geochemically important functional genes.

The use of environmental genomics is exploding in the field of microbial ecology for the study of both prokaryotic and eukaryotic organisms. At present it is mostly discovery based science but has promise to yield better understanding of underlying mechanisms in biogeochemical processes. It is recommended that microbial and molecular ecologists be included in the time-series and process studies in order to begin to elucidate temporal and spatial variability of microbial community structure as well as functional diversity.

Autonomous carbon flux monitoring: 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: Organic compounds, radionuclides, and trace 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.

Lagrangian 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 and Kozerski, 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 (Stanley 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. Preliminary studies have been conducted on using natural, radioactive phosphorus isotopes to quantify upper-ocean nutrient cycling. 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. The application of these approaches throughout the mesopelagic zone will provide more accurate estimates of particle transport efficiency through this depth horizon.

Metabolic rates and remineralization: Tracers of microbial metabolic activity (adenine, thymidine, leucine, electron transport system measurements) already exist; however, rate measurements within the mesopelagic zone are sparse. Methodologies 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 versus respiration rates. Another approach is to look at the products of particle decomposition (i.e., AOU). The distribution of bioactive tracers in the mesopelagic 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.

Stable isotopes: Data on the distribution of bioactive tracers in the oceans have long been a primary source of information for reconstructing the carbon and nutrient cycles in the oceans. Contributions of these studies include, for example, constraints on upper ocean carbon fluxes in the subtropical gyres based on O_2 distributions. A serious limitation to the interpretation of concentration measurements is that one cannot accurately separate the effects of competing processes on the distributions. Stable isotope distributions of carbon, nitrate, O_2, and SiO_2 can be used to partition the impact of photosynthesis and respiration, consumption and production, nutrient utilization and resupply by mixing, and production (or consumption) and gas exchange. By combining isotopes and concentrations, the absolute values of the competing rates can be determined.

Reference Material Development and Support: Accuracy in measuring oceanographic parameters requires frequent calibration against reference materials. Production of the reliable data sets or long-term baseline studies that are essential to verify global change and oceanic stability is impossible without reference materials. Reference materials are homogeneous, stable substances whose properties are sufficiently well established to be useful in calibrating analytical instruments, validating measurement techniques, and assigning accurate values. Regular use of such materials provides a much needed basis for interlaboratory and international comparison of results, making it possible to acquire accurate, meaningful global data sets that can be used to study problems requiring observations over large space and time scales. Recently (NRC, 2002), the Oceans Studies board of the National Research Council sponsored a study of Chemical Reference Materials. That report sets priorities for development and support of reference materials for oceanographic programs requiring interlaboratory and international comparisons. OCCC clearly will need the DIC and DOC reference materials currently available, as well as the sea water nutrient, trace metal, radionuclide, and solid matrix-based reference materials suggested. The report is available for sale from the National Academy Press or free electronically (http://www.nap.edu).

9.2 Autonomous Sensors and Platforms

As detailed below, recent advances on autonomous sensors and platforms offer to revolutionize the field of ocean biogeochemistry over the next decade, and these new technologies should be incorporated wherever appropriate in the design of OCCC observing systems and process studies. A balanced strategy including shipboard studies, autonomous instrumented platforms and satellites is required (Figure 8), however, given that not all properties are accessible to in situ autonomous or remote sensing techniques and 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 (e.g., subsurface ocean).

Platforms

High powered systems: The attractions of high power systems include the diverse suite of potential measurements (many of which can not yet be adapted to lower power platforms) multiple interdisciplinary sensors, high speed communication with shore, recovery of instruments for post-deployment calibration, storage of water samples for ship or shore-based analysis, and the validation against shipboard measurements.

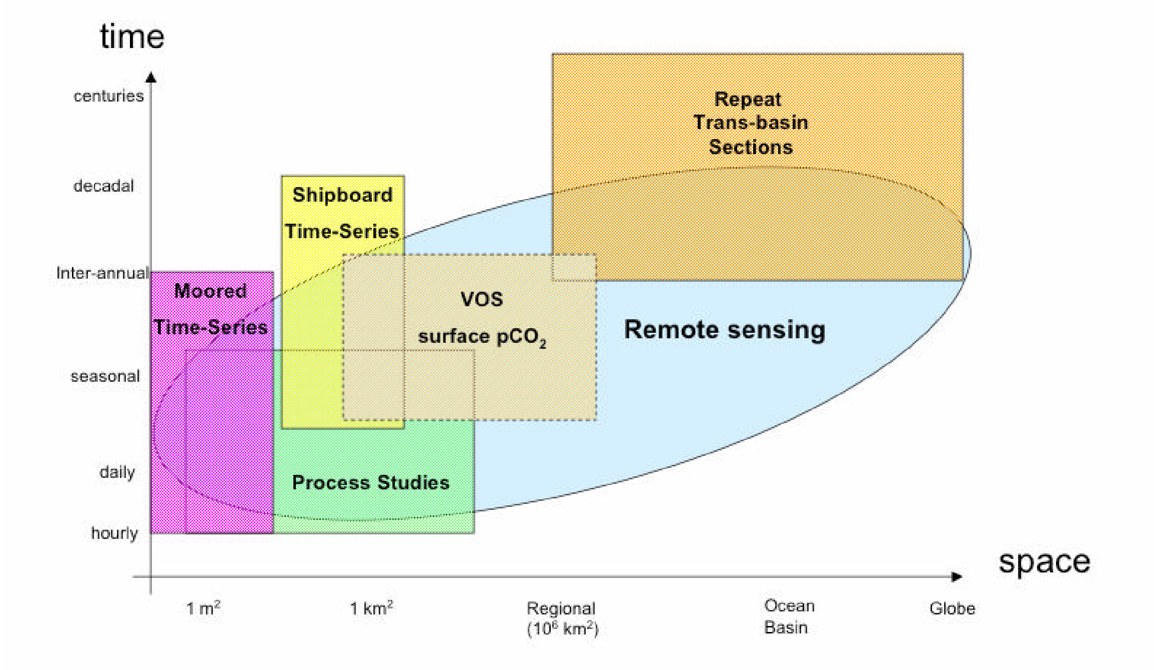

Figure 8: Time-space diagram highlighting the relationship among the different sampling platforms and approaches.

Moorings and cabled observatories: Deep-sea and coastal 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/water 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 and large open ocean spar buoys, all of which offer the potential for high power, high speed, real-time two communication capabilities, and integrated, multi-instrument systems (Glen and Dickey, 2002; NSF ORION ocean observatory).

Towed devices: Ship-based, towed devices such as the undulating SeaSoar and optical plankton counters provide the capability for rapid, high resolution (~1 km scale) mapping of the upper several hundred meters of the ocean. They have proven invaluable for determining local and regional structure around process studies, for characterization of mesoscale and submesocale ocean variability, and as part of basin-scale transects. The addition of continuous water collection capabilities via pumping from the towed body to ship laboratories greatly expands the suite of chemical and biological variables that can be measured over the upper water column via ship surveys.

AUVs: 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: 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 meteorological 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. The CARIOCA buoys (CARbon Interface OCean Atmosphere) (Hood et al., 1999; Bakker et al., 2001; Hood et al., 2001a,b) have shown some success, and WOCE- style drifters enhanced with passive radiance and irradiance sensors have been 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; http://www-argo.ucsd.edu/), 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 the time the float spends in the euphotic zone 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 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.

Carbon, oxygen and nutrient sensors

Progress on in situ 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 aggressive 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: for 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 ? pCO_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, 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 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 constants from minutes to seconds in order to meet profiling applications.

DOC: Measurements of dissolved organic carbon currently 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 standardization of optical specifics of these instruments across manufacturers (e.g., receiver acceptance angle) and a 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 transmissometer deployment now as a routine 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 commercialized 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.

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 9.1).

Dissolved O_2 sensors: Measurements of dissolved O_2 contain a wealth of information on marine biological and physical processes (e.g., Redfield, 1948; Broecker and Peng, 1982). 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 air-sea ΔpCO_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.

Continuous atmospheric CO_2 systems: Atmospheric CO_2 concentration is measured by many of the ΔpCO_2 systems currently available as part of research ship based underway surveys. At present, autonomous moored systems do not have sufficient precision or accuracy to meet the needs of the atmospheric community. Developing such a seaworthy system will require more careful temperature and pressure control as well as frequent field calibration using on-board CO2 gas standards tied back into the international standards network such as that maintained by NOAA/CMDL (http://www.cmdl.noaa.gov). Development on moored instrumentation could be done in conjunction with improvements to the atmospheric measurements from ship-based underway systems, which need to be maintained and added to other research and VOS platforms where feasible.

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 or P in profiling mode.

Reactive micronutrients: There is currently no means to assess Fe directly in the water column, particularly at 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 be 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 system 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. A program of professional or /or volunteer “riders” on ships of opportunity has the potential to greatly extend the scientific return from use of these vessels.

9.3 Remote Sensing

Remote sensing technology development falls into several categories including utilization of operational satellites, advanced remote sensing systems, improved atmospheric correction schemes, new and/or improved bio-optical algorithms for carbon constituents, and improvements in field measurement protocols and optical instruments. All categories require continued support to achieve the observational needs of a comprehensive global ocean carbon program.

Operational satellites: Many of the remotely sensed, oceanographic variables (e.g., SSH, SST, wind speed, ocean color) that are now routinely used in ocean carbon research are being transitioned from research data into operational products, much has been done for weather satellites. While this has the advantage of guarantteeing continuous measurements into the future, potentially crititical issues arise as to whether the operational data will be suitable for many climate related applications, which require the continuity of calibrated/validated, stable, and high precision/accuracy observations over many years if not decades. The concept under development of “Climate Data Records” is an attempt to address these problems but is a less-than-perfect assurance that the operational products will retain the important capabilities of existing remote sensing sensors/platforms. The community must continue to express their need for the appropriate types (e.g. wind vector versus speed) and accuracies of ocean measurements. Ongoing dialogue between the remote sensing development and user communities is crucial to optimally utilize existing data and to guarantee high quality data records for the future.

Advanced remote sensing systems. At present, several new measurement techniques for carbon cycle related observations are being studied. These include an airborne dual pulse and probe laser fluorometer, a laboratory laser concept for measuring bicarbonate concentration, and a particulate organic carbon (POC) lidar system. The dual pulse and probe lidar is being tested on a small aircraft to measure phytoplankton photosystem efficiency and can be used to support field experiments and routine surveys. A second generation version could optimize the design and incorporate additional experimental capabilities for pigment and phytoplankton species classification. Finally, the shortest wavelength band on SeaWiFS and MODIS is 412 nm. Measurements of ocean reflectance down to 340 nm are being considered for future missions to utilize strong absorption properties of various pigments and dissolved constituents. This poses new challenges for radiometer design and calibration (ground and on-orbit) that need to be addressed.

Two sensors recently funded under NASA's Earth System Science Pathfinder (ESSP) Program are directly applicable to carbon cycle science. The two sensors have planned launches in 2006-2007. The Orbiting Carbon Observatory (OCO) will provide full atmospheric column concentration of $CO_{2,}$ while Aquarius will measure sea surface salinity. The ESSP Program can be seen as a viable, though highly competitive, strategy to launch pathfinder missions, such as those needed to study coastal or sea-land interactions.

A*tmospheric correction algorithms.* Absorbing aerosols remain problematic in current SeaWiFS and MODIS atmospheric correction algorithms. Dust, smoke, and pollution can greatly limit the accuracy of the derived products not only in coastal areas, but also over extended areas far offshore. Continued evaluation of schemes to detect and correct for these aerosol types is needed. Also, advanced satellite measurement schemes for quantifying the dust concentrations and mineral iron content of should also be explored to estimate iron wet and dry deposition. With regard to satellite measurements in the UV, deriving accurate estimates of water-leaving radiance below 412 nm will require a new, or at least a much improved, approach to atmospheric correction than is presently being used for SeaWiFS and MODIS processing.

Bio-optical algorithms. Currently, only a limited number of carbon related products are produced operationally by instruments like SeaWiFS (chlorophyll-a) and MODIS (chlorophyll-a, primary production, and calcite). Of these, only chlorophyll-a has been extensively validated using post-launch comparisons with in situ data. A substantial level of effort is needed to verify and improve the calcite and primary production algorithms. Algorithms for other parameters such as color dissolved organic matter (CDOM) and POC are being developed but have not been the focus of a broad based validation effort. Site-specific algorithms for dissolved organic carbon (DOC) in river plumes, for instance, may be feasible as well, but require a diverse database of DOC and optical properties for algorithm evaluation.

Measurement protocols and in situ instruments: The methodologies for collecting accurate apparent and inherent optical properties, or so-called measurement protocols, needs to be continued. The SeaWiFS and SIMBIOS Projects have supported the development of a set of such protocols over the past decade, but a number of issues remain, especially in coastal regions where water clarity limits the accuracy of in-water radiometry. Also, as new carbon parameters of interest are considered for satellite products (e.g., POC), refinements in measurement accuracies will be needed just as has been the case for chlorophyll-a, the primary derived product from SeaWiFS and MODIS. Similarly, improved designs for in-water and above surface radiometers and absorption and scattering meters need to be supported. All are critical measurements for improving reflectance models, empirical bio-optical algorithms, and post-launch validation.

10 Enabling Activities

The OCCC program will require substantial effort in terms of data management and cooperation with other carbon cycle, oceanographic and climate programs (both nationally and internationally). It is also important for the program to include workshops and meetings for scientific communication as well as to support actively outreach activities to make ocean carbon system information available to policy makers, educators, and the general public. This section presents the foundation for developing each of enabling activities. A management framework for coordinating and integrating the many efforts within OCCC is also presented.

10.1 Data Management and Data Availability

Data management within OCCC requires explicit 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 OCCC 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 the ocean Repeat Hydrography (Section 5.1) and VOS pCO_2 (Section 5.2) surveys (Feely and Sabine, 2002). The meeting produced a data management plan to establish a standardized scheme for data collection, quality control, rapid access, and archival, which was largely built on the experience gained form previous ocean data programs such as U.S. JGOFS and WOCE. The plan provides firm groundwork for an ocean carbon 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 inorganic carbon system and required ancillary data from both field programs and automated sensors.

Process Study Team. Similar to the CO_2 Science Team, this committee will set standards for collection, reporting and quality control of the more diverse suite of chemical, physical, and biological data from process studies and the observing network.

Standards and Reference Materials Team. This group will be responsible for establishing protocols for reference materials, intercomparisons, and field protocols.

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 overall U.S. GCRP Carbon Science programs, where there is a strong desire to integrate data from ocean, atmosphere and terrestrial studies across, for example, the OCCC and NACP. 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 U.S. 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 U.S. Climate Change Science Program (CCSP; Mahoney, 2003). 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 OCCC 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 OCCC 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 9).

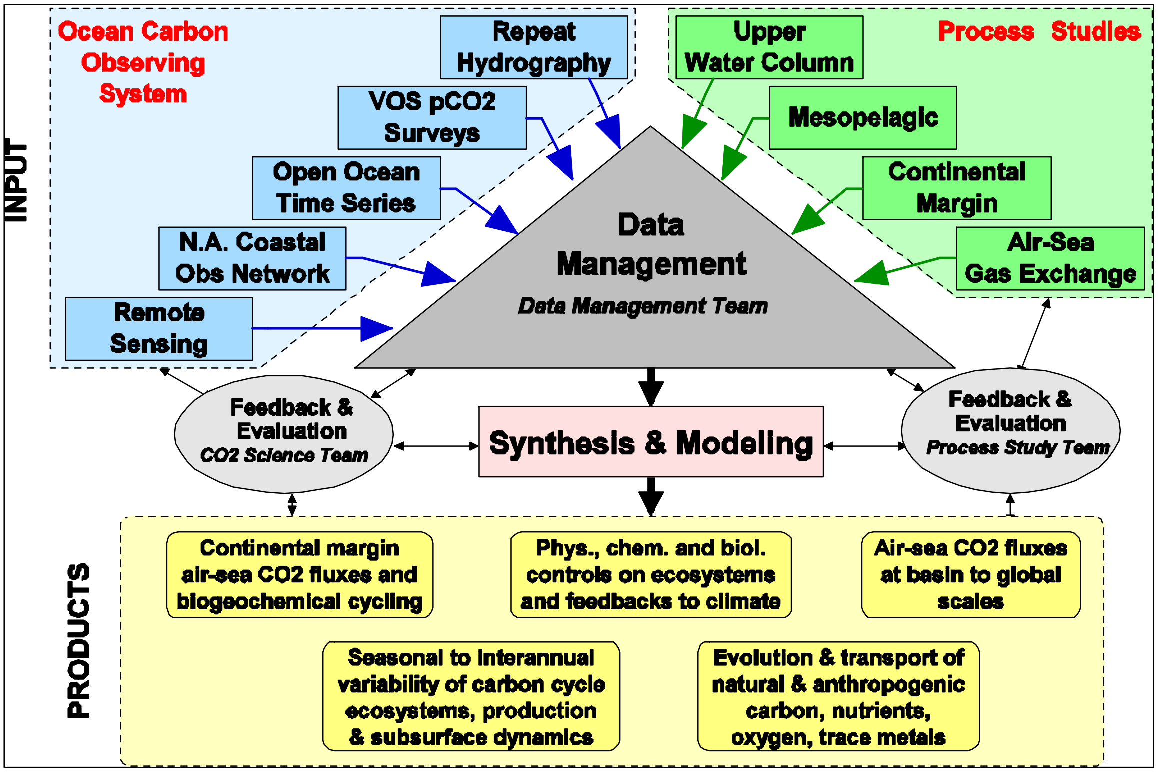

Figure 9: Data management schematic for OCCC.

10.2 Synergy with US Oceanographic, Carbon and Climate Programs

The Ocean Carbon and Climate Change program will benefit from strong interactions with a variety of related oceanographic, carbon cycle, and climate programs. In some cases the synergies can best be realized through mutual scientific interactions and communication such as joint workshops and steering committee meetings. In other cases, the synergy can extend as far as the sharing of common sampling platforms and detailed coordination of specific field campaigns and observing systems.

NACP

The overall scientific objectives of the OCCC and North American Carbon Program (NACP) (Wofsy and Harriss, 2002) are closely linked, with particular overlap on addressing Goal 1 (North American terrestrial carbon sink) of the Carbon Cycle Science Plan (Sarmiento and Wofsy, 1999). The NACP implementation strategy (Denning et al., 2004) is organized around four major questions involved in diagnosing the size of the net carbon sink for North America, attributing the sink to particular processes, developing predictive models for the future behavior of the sink, and building decision support tools for policy makers. Oceanic research pervades all four of these elements.

Topics of particular synergy between OCCC and NACP involve: the lateral exchanges at the land-ocean interface (e.g., rivers, estuaries, groundwater, atmospheric deposition); biogeochemical dynamics on the continental margin; and the air-sea fluxes of CO_2, O_2 and other trace gases from the coastal ocean and adjacent open-ocean North Atlantic, North Pacific and Arctic basins. The rationale for the first two items is obvious, as they are needed to close the carbon budget for the North American continent. The gas fluxes are important because they provide key upstream and downstream boundary conditions for the top-down, atmospheric constraints that will be used in NACP to estimate regional terrestrial CO_2 sink patterns.

Many of the detailed science recommendations described here for OCCC are also, therefore, directly applicable to NACP. In some cases, the oceanic studies required for the success of the NACP will be carried out independently by NACP or as joint OCCC/NACP projects; this is particularly true for land-ocean interactions and the continental margins. Specific relevant OCCC components include the North American coastal observing network (Section 5.4), the continental margin biogeochemistry process studies (Section 6.2) and parts of remote sensing (Section 5.5), air-sea gas exchange (Section 6.3), synthesis and numerical modeling (Section 8), and methods and technology development (Section 9). In other cases, a good example being the basin-scale gas fluxes, OCCC will develop and share with NACP targeted data products and scientific understanding relevant to NACP objectives. The two programs will coordinate on defining overall requirements (e.g., time/space frequency of sampling; measurement suite; coordination with NACP observing system and field campaigns), with OCCC responsible for implementation and NACP for integration and synthesis with other atmospheric and terrestrial data. Relevant OCCC components in this regard include the VOS pCO_2 surveys (Section 5.2) and parts of open-ocean time-series (Section 5.3), remote sensing (Section 5.5), upper-water column process studies (Section 6.1), air-sea gas exchange (Section 6.3), synthesis and numerical modeling (Section 8), and methods and technology development (Section 9).

There is already a fruitful, on-going relationship between OCCC and NACP to ensure consistency in the recommendations of the two implementation strategies. Continued coordination will be required through the planning, implementation, and synthesis phases of specific field and modeling studies. This can be accomplished though close interaction at several levels including mutual representation on program steering committees, targeted scientific workshops, and joint campaigns, process studies and observing systems.

CLIVAR

The goals of the Climate Variability and Predictability program (CLIVAR), within the World Climate Research Programme (WCRP) are extremely relevant to the goals of the OCCC. The goal of CLIVAR is to investigate the physical and dynamical processes in the climate system occurring on seasonal to centennial time scales. The US component of CLIVAR focuses on these processes as they affect the United States. There is a strong oceanic component of US CLIVAR, and therefore there should be a close relationship between US CLIVAR and OCCC. US CLIVAR focuses on physical processes, while the goals of OCCC encompass all processes, physical as well as biogeochemical, which affect the oceanic limb of the carbon cycle. The ocean circulation and its interaction with climate change are of first order importance to the ocean carbon cycle. US CLIVAR is in various stages of development and execution of studies of climate-relevant ocean circulation processes in the North Atlantic, Pacific, and Southern Ocean. The present implementation plan is complementary to US CLIVAR in the general sense that it focuses on carbon inventories, air-sea fluxes of carbon and internal sources and sinks of carbon, leaving most ocean circulation problems to CLIVAR and other programs in ocean circulation. Clearly, however, a close, active, ongoing coordination between US CLIVAR and OCCC is necessary for the completeness of both programs.

Arctic Programs

Many ongoing and planned carbon-related projects are occurring in the Arctic. For example, the Western Arctic Shelf-Basin Interactions (SBI) project (http://sbi.utk.edu), funded through the National Science Foundation and the Office of Naval Research, is the largest global change, carbon-driven project in the Arctic at the current time. The major goal of SBI is to investigate the production, transformation, and fate of carbon at the shelf-slope interface in the Arctic as a prelude to understanding the impacts of a potential warming of the Arctic. An accumulated body of research indicates that climate change will significantly impact the physical and biological linkages between the Arctic shelves and adjacent ocean basins. Phase I of SBI used retrospective research and analyses, opportunistic sampling studies, and modeling to prepare for field work in the Chukchi and Beaufort seas. The second phase of the SBI project (2002-2006) involves 40 Principal Investigators on 14 integrated projects working in the Bering Strait region and over the outer shelf, shelf break, and upper slope of the Chukchi and Beaufort seas and into the Arctic Basin. The final SBI Phase III (2007-2009) will focus on development of Pan Arctic models suitable for simulating scenarios of the impacts of climate change on shelf-basin interactions.

Long-term observations are critical for understanding the baseline processes occurring related to ecosystem processes and the physical driving forces for the changes we are beginning to see in the Arctic. Currently studies of the hydrographics and biogeochemical cycling through the northern Bering Sea and Chukchi Sea are being undertaken both from ship-based and land-based facilities as part of the Bering Strait Environmental Observatory (BSEO), http://arctic.bio.utk.edu). The North Pole Environmental Observatory primarily focuses on oceanographic and ice dynamics at the pole, with some hydrochemical samples (http://psc.apl.washington.edu/northpole/index.html).

The Study of Environmental Arctic Change (SEARCH) is motivated by the desire to understand the complex of significant, pan-Arctic, interrelated, atmospheric, oceanic, and terrestrial changes that has occurred in recent decades. The research community, working with the SEARCH Science Steering Committee (SSC), has developed the SEARCH Science Plan, which describes the observed changes and advances key hypotheses. The SEARCH Science Implementation Strategy is available (in addition to the Science Plan) at http://psc.apl.washington.edu/search/index.html. It describes the activities of SEARCH in eight interdisciplinary activity areas that closely interact with each other, with the Distributed Marine Observatories (DMO) activity area of importance to maintaining long-term studies in the region.

The are other large national and international carbon-relevanton ongoing and planned projects, such as studies of the riverine influence on the Arctic Ocean (Pan-Arctic River Transport of Nutrients, Organic Matter and Suspended Sediments, PARTNERS), Ocean Exploration studies of NOAA, the Land-Shelf Initiative (LSI) to investigate carbon and other material transport from the land's edge through the nearshore coastal zone (http://arctic.bio.utk.edu), and the Canadian Arctic Shelf Exchange Study (CASES). Based on changes being observed in the Arctic, International Arctic Shelf-Basin Exchange (SBE) working group of the Arctic Ocean Sciences Board is proposing an internationally-coordinated project to understand key parameters at the shelf break in the Arctic to be measured simultaneously during a set period of time as part of the 2007/08 International Polar Year.

10.3 International Cooperation and Linkages

Introduction

Over the last four decades, governments have increasingly recognized the necessity of working together on ocean issues and have established a number of international conventions that specifically call on nations to address the role of the ocean carbon system and climate change through a coordinated mechanism of research and observation (see inset). Since the dawn of climate research, scientists have recognized the critical nature of international cooperation and have actively pursued international partnerships through their national research programs. Uniting these top-down and bottom-up drivers for international cooperation are regional and international programs for ocean carbon research and observations. Most of the programs containing ocean carbon research are part of larger "earth system" research or observation network with a complex array of partnerships and sponsorships. Because there is no single, comprehensive ocean carbon research program, the need for communication and coordination between the existing programs is critical for developing the type of cooperative research and observation network needed to provide a global view of ocean carbon.

Frameworks for Research and Observation Cooperation

Figure 10 illustrates the principle relationships between the major ocean carbon research and observation efforts. The principle drivers for cooperation are governments, acting through various United Nations and intergovernmental organizations or international NGOs, and individual scientists and national agencies seeking international collaboration on specific research topics. Governments develop international conventions and give mandates to intergovernmental agencies or international organizations to carry out coordinated research and observations. Figure 10 (box 1) also shows the principle international organizations sponsoring ocean carbon research and observation programs, which include the International Geosphere – Biosphere Program (IGBP), the World Climate Research Program (WCRP), and ICSU's Scientific Committee on Oceanic Research (SCOR). The intergovernmental organizations that work closely with these programs are the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the World Meteorological Organization (as co-sponsors of WCRP). These organizations most often co-sponsor projects in various combinations to address particular large-scale issues. For example, the IGBP and WCRP, together with the International Human Dimensions Program (IHDP), have established 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 and the interactions between them. SCOR and the IOC have sponsored a joint Advisory Panel on Ocean CO_2 since the early 1980's. In order to coordinate the ocean carbon research and observations for the Global Carbon Project, the GCP has teamed up with the SCOR-IOC CO_2 Panel to develop a pilot project called the International Ocean Carbon Coordination Project (IOCCP). The GCP will seek similar partnerships for coordination of the atmospheric and terrestrial domains.

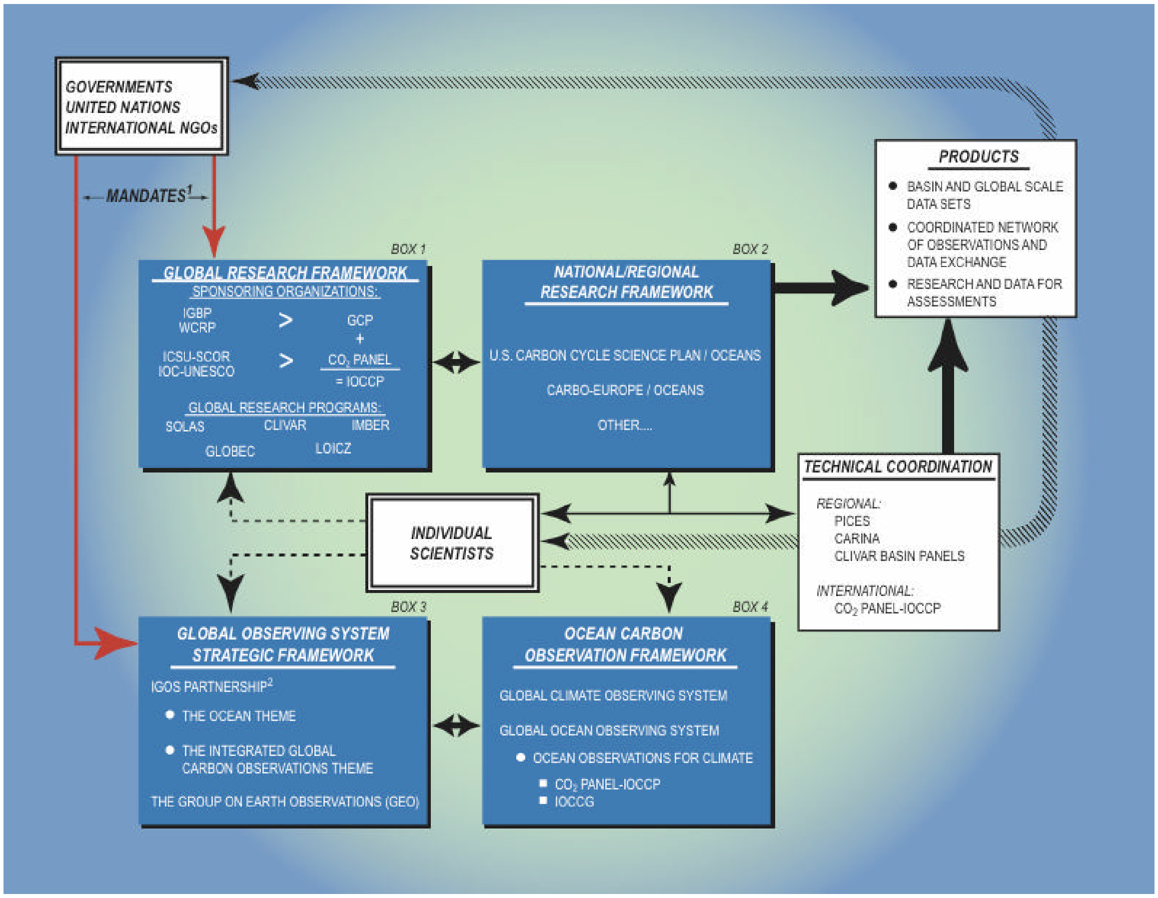

Figure 10: Schematic of international science coordination framework relevant to ocean carbon research.

Also shown in Figure 10 (box 1) are the major global research programs that address different issues of ocean carbon. Each of the programs addresses a specific issue of ocean carbon within the framework of other ocean science topics. For example, SOLAS focuses on the air-sea exchange of CO_2, CLIVAR focuses on large scale uptake and transport of carbon, IMBER focuses on carbon transport, storage, and transformations, LOICZ focuses on coastal carbon fluxes, and GLOBEC focuses on carbon flow through ecosystems in the higher trophic levels.

While these programs create a thorough coverage of most ocean carbon issues, there is a still a need to develop a comprehensive carbon cycle research and observation framework. Several national and regional groups are in the process of developing such unified research and implementation strategies (Figure 10, box 2). For example, the U.S. Carbon Cycle Science Plan (Sarmiento and Wofsy, 1998) and this OCCC report represent one such effort. In Europe, a coordinated framework for ocean carbon research is being developed as part of the Carbo-Europe effort. Individual scientists and national agencies determine the priority areas and drive the research that will be carried out under these frameworks.

In parallel to and building on these global research initiatives is the development of an earth observing system (Figure 10, box 3), mandated by governments through international conventions and carried out by UN agencies and other intergovernmental bodies. The Integrated Global Observing Strategy (IGOS) Partnership, which brings together the global research programs from Figure 10, box 1, the global observing systems and their sponsor agencies, and the national space agencies to develop thematic strategies that provide a framework for international cooperation and resource allocation. The IGOS-P has developed an Ocean Theme for coordinated in situ and satellite approaches for ocean monitoring, including ocean carbon, and has recently developed an Integrated Global Carbon Observation Theme, which also includes an ocean carbon observation strategy consistent with the Ocean Theme and also with observation strategies from the atmospheric and terrestrial domains. To further strengthen the governmental commitment to the development of a global observing system, Ministers and Senior Level officials from the G-8 and other countries that fund or use observing systems held an Earth Observation Summit in 2003 and established the Group on Earth Observations (GEO), which will develop a 10-year implementation plan for a coordinated, comprehensive, and sustained Earth observation system.

These high-level groups provide a mechanism for developing integrated strategies between the in situ and satellite observation communities and for obtaining commitments from governments to implement them. The actual management and development of those networks are carried out by the Global Observing Systems (Figure 10, box 4). The ocean component for climate change study is sponsored jointly by the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS), with strategy and coordination managed by the Ocean Observations Panel for Climate (OOPC). For ocean carbon expertise, the OOPC calls on the SCOR-IOC Advisory Panel on Ocean CO_2 and its International Ocean Carbon Coordination Project (IOCCP) for advice and coordination. For ocean color expertise, these groups rely on the International

Ocean-Colour Coordination Group (IOCCG) for priorities, strategies, and implementation coordination.

From Strategic Frameworks to Products

Through these frameworks we have developed i) plans for comprehensive carbon research at the national and regional level (e.g., U.S. Carbon Cycle Science Plan), with the ocean carbon components integrated into these strategies; and ii) plans for comprehensive global observations at the international level (e.g., GCOS and GOOS), with ocean carbon observations integrated into the ocean and climate system strategies. This provides a necessary framework for national or regional agencies to identify priorities, set research agendas, and implement programs that, when combined with those of other nations, can create a global network of research and observations. However, data products are not produced from strategies but rather from the results of individual scientists and research programs, and it is at this level that technical coordination must be focused.

A number of regional and international groups already exist to provide technical coordination (Figure 10). Regionally, there is the North Pacific Marine Science Organization (PICES) and their working groups that deal with ocean carbon issues, and the Carbon in the Atlantic (CARINA) program that brings together scientists in the Atlantic region for data sharing and collaboration. Similar groups for the Indian and Southern oceans are under discussion, and may be carried out initially in collaboration with the CLIVAR basin panels. At the international level, the IOCCP has been developed to serve as a central communication and coordination mechanism between national and regional groups and international programs. The first steps in creating a system of technical coordination are to document the relevant activities being carried out under various programs and then to coordinate observation activities, data sharing, synthesis activities, and data product development. The IOCCP work is being carried out through the development of a web site with continuously updated information on observation programs, wide distribution of a bimonthly email-based newsletter, and targeted workshops to address field program coordination, intercomparison experiments, best practices development and training, data format agreements, data sharing, and joint data synthesis projects.

With sufficient commitment, these coordination activities can lead to the development of a cooperative research and observation network capable of producing regular basin and global scale data products for research and assessment and decision-making tools for policy-makers. As our understanding of the ocean carbon system deepens and our observation techniques improve, we can begin to transition certain elements of this observation network to sustained systems of the global observing system for climate research. This step-wise, bottom-up approach allows us to produce the required global scale data products now while ensuring maximum flexibility for scientists and national agencies in identifying research and observation priorities and maintaining the highest quality of ocean carbon data during the transition to a more operational system.

10.4 Workshops and Scientific Interactions

Science, coordination, and planning workshops are integral to every stage of the OCCC program, from planning of field experiments to analysis of results and dissemination of information. Workshops will be essential 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 mechanisms for communicating with policymakers, educators, and the general public. Data analysis workshops will be designed to bring scientists working on laboratory and field data, remote sensing products, and models together to address specific problems. As discoveries are brought to light, additional workshops will be required to tackle new scientific challenges. Table 6 lists the types of workshops that will be included in the OCCC program. These will be coordinated with the education and outreach activities (Section 10.5) and within the overall OCCC management framework (section 10.6).

10.5 Education and Outreach

The U.S. Climate Change Science Program Strategic Plan (Mahoney, 2003) 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 decision makers; 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 OCCC because it influences policy making at regional, national and international scales. OCCC will provide research results to the Global Change Research Information Office for further dissemination to policymakers and will participate in U.S. 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. OCCC 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.

Table 6. Types of workshops and meetings proposed for the OCCC.

Workshop/Meeting	***Main Attendees***	***Main Objectives***
Scientific Steering Committee meeting		
Ocean carbon science workshop	Currently funded PIs from repeat hydrography, VOS, and time-series stations	Build community support for OCCC Refine program elements Refine plans for process studies
Pre-field study workshop	Observationalists and data managers	Data collection standards: protocols, reference materials; intercomparisons Data reporting standards and data QC
Post-field study workshop	Observationalists and data managers	Data analysis
Synthesis and modeling	Modelers, observationalists, remote sensing specialists	Data synthesis and model development
Data management workshop	Data managers and representatives from field studies, autonomous studies, remote sensing, modelers etc.	Facilitate data reporting Implemention and updating of data collection and delivery system
International workshops	National and international representatives from various ocean research programs	Dissemination of results Coordination of joint or complementary efforts
Education and outreach	Observationalists, modelers, educators, policy makers	Develop avenues for providing information to various sectors of society, from policy makers to the general public
Special workshops	Observationalists and modelers	Address specific problems or new research challenges
Annual scientific meeting	Scientific investigators, program managers from funding agencies, invited speakers from outside OCCC, invited educators, students and policy-makers	Dissemination of information, address of specific problems, communication with educators and policy-makers

Web-based education has become increasingly popular in K-12 classrooms. In concert with the call in the U.S. CCSP plan (Mahoney, 2003) to coordinate and streamline outreach activities across the various agencies, OCCC 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. OCCC will work within the overall U.S. 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 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 program.

10.6 Management Framework

The research components of the OCCC 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 OCCC 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 in 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 (Table 6) 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 (e.g., 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 (Section 5.4; in conjunction with the NACP) and the North Atlantic, North and Equatorial Pacific process studies (Section 6).

During the phase I period of OCCC (Figure 1), a variety of other national and international oceanographic programs will carry out relevant studies in the North Atlantic, North Pacific and Southern Ocean. The OCCC should maintain ties with these programs (e.g., CLIVAR) to ensure that the program capitalizes on potential leverage opportunities in planning OCCC 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 system 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, OCCC must take account of those efforts in designing any future US program to study the carbon system in the Southern Ocean.

Recommendations

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

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

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

11 Scientific Products and Payoffs

Anticipated scientific products and payoffs from OCCC are summarized in Table 7 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 OCCC are achievable only by combining results from two or more implementation elements. The specific recommendations and rough cost estimates for Phase-1 of the OCCC program are summarized in Table 8.

Table 7 CCSP-Oceans: Products, Payoffs, and Program Elements

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, North and Equatorial 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)
Southern ocean pilot studies	(section 7)
Data assimilation and hindcast modeling	(section 8)
Open-ocean time-series	(section 5.3)
Remote sensing	(section 5.5)
Upper water & mesopelagic process studies	(section 6.1)
Southern Ocean pilot studies	(section 7)
Data assimilation and hindcast modeling	(section 8)
VOS pCO_2 surveys	(section 5.2)
North American coastal observing network	(section 5.4)
Continental margin process studies	(section 6.2)
Gas exchange process studies	(section 6.3)
-Physical, chemical, and biological controls on present and future marine ecosystems and ocean carbon dynamics including biogeochemical responses to and feedbacks on climate change	
Upper water & mesopelagic process studies	(section 6.1)
Continental margin biogeochemistry	(section 6.2)
Numerical synthesis and modeling	(section 7 & 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)
Technology development	(section 9)
-Communication of research findings and decision support tools to stakeholders (scientific community, policy makers, resource managers, students, general public)	
Data management	(section 10.1)
U.S. & International coordination and linkage	(section 10.2 & 10.3)
Workshops and education outreach	(section 10.4 & 10.5)
Scientific oversight and management	(section 10.6)

Table 8 Specific Recommendations and Cost Estimates for OCCC Phase-1

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)	$5-6 M/yr
continuation/augmentation of BATS, HOT, and EqPac	
new time-series 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 & Mesopelagic (section 6.1)	$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 6.2)	$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 6.3)	$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)	$4-5 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 8 Specific Recommendations and Cost Estimates for OCCC Phase-1 (cont.)	
Technology development (section 9)	$6-8 M/yr
chemical biological techniques *in situ* carbon system sensors integration with autonomous platforms remote sensing algorithms & field testing reference standards	
Data Management (section 10.1)	$1-1.5 M/yr
data processing and quality control distribution and archival data Integration at International level	
U.S. & International coordination and linkages (section 10.2 & 10.3)	$0.25 M/y
Workshops and educations outreach (section 10.4 & 10.5)	$0.5 M/yr
Management framework (section 10.6)	$0.5 M/yr
planning office and steering committee	

Note: budget estimates provided for existing and phase 1 (2005-2009) elements of the OCCC program. Ongoing and recently funded elements of the program are marked accordingly in brackets [$ M/yr]. The full budget estimates would require new money beyond that currently spent on ocean carbon research within the US.

12 References

Archer, D., Kheshgi H., and Maier-Reimer E. (1998) Dynamics of fossil fuel CO_2 neutralization by marine $CaCO_3$. *Global Biogeochem. Cycles* 12 (2): 259-276.

Argo Science Team (1998) On the design and implementation of Argo: an initial plan for a global array of profiling floats. International CLIVAR Project Office Report 21, GODAE Report 5. GODAE International Project Office, Melbourne Australia, 32 pp.

Armstrong, R. A., C. Lee, J. I. Hedges, S. Honjo and S. G. Wakeham (2002) A new, mechanistic model for organic carbon fluxes in the ocean based on the quantitative association of POC with ballast minerals. *Deep-Sea Res*., 49, 219-236.

Bakker, DCE, Etcheto J, Boutin J, Merlivat L. (2001) Variability of surface water fCO_2 during seasonal upwelling in the equatorial Atlantic Ocean as observed by a drifting buoy. *J. Geophys. Res.-Oceans* 106 (C5): 9241-9253.

Bates, N.R. (2001) Interannual variability of oceanic CO_2 and biogeochemical properties in the Western North Atlantic subtropical gyre. *Deep Sea Res. II* 48 (8-9): 1507-1528/

Bates, NR, Pequignet A.C., Johnson R.J., Gruber N. (2002) A short-term sink for atmospheric CO_2 in subtropical mode water of the North Atlantic Ocean. *Nature* 420 (6915): 489-493.

Behrenfeld, M., J. Randerson, C. McClain, G. Feldman, S. Los, C. Tucker, P. Falkowski, C. Field, R. Frouin, W. Esaias, D. Kolber, and N. Pollack, (2001), Temporal changes in the photosynthetic biosphere, *Science*, 291, 2594-2597.

Bender, M., S. Doney, R.A. Feely, I. Fung, N. Gruber, D.E. Harrison, R. Keeling, J.K. Moore, J. Sarmiento, E. Sarachik, B. Stephens, T. Takahashi, P. Tans, and R. Wanninkhof (2002): A large-scale CO_2 observing plan: In situ oceans and atmosphere (LSCOP). NOAA OAR Special Report, 201 pp.

Berelson, W. M. (2001). The flux of particulate organic carbon into the ocean interior: A comparison of four US JGOFS regional studies. *Oceanogr*. 14: 59-67.

Bishop, J.K.B. and W.B. Rossow (1991) Spatial and temporal variability of global surface solar irradiance. *JGR-Oceans* 96 (C9): 16839-16858.

Bishop, J.K.B., R.E. Davis and J.T. Sherman (2002). Robotic observations of dust storm enhancement of carbon biomass in the North Pacific. *Science* 298: 817-821.

Bock, E.J., Hara T., Frew N.M., McGillis W.R. (1999) Relationship between air-sea gas transfer and short wind waves. *J. Geophys. Res.-Oceans* 104 (C11): 25821-25831.

Boehme, S.E., Sabine, C.L., Reimers, C.E., 1998. CO_2 fluxes from a coastal transect: a time-series approach. *Marine Chemistry, 63*, 49–67.

Bopp, L., Monfray P., Aumont O., Dufresne J.L., Le Treut H., Madec G., Terray L., Orr J.C. (2001) Potential impact of climate change on marine export production. *Global Biogeochem. Cycles* 15 (1): 81-99.

Bopp, L., C. LeQuere, M. Heimann, A. Manning, and P. Monfray (2002): Climate induced oceanic oxygen fluxes: implications for the contemporary carbon budget. *Global Biogeochem. Cycles* 16(2), 10.1029/2001GB001445.

Boyd, P.W. and S.C. Doney (2002) Modelling regional responses by marine pelagic ecosystems to global climate change. *Geophys. Res. Lett.* 29 (16), 53-1 to 53-4, doi:10.1029/2001GL014130.

Boyd, P. and S.C. Doney, (2003) The impact of climate change and feedback process on the ocean carbon cycle. *Ocean Biogeochemistry*, ed. M. Fasham, Springer, 157-193.

Boyd, P. W., and C. S. Law, (2001) The Southern Ocean Iron Release Experiment (SOIREE) – introduction and summary, *Deep Sea Res. II,* 48, 2425-2438.

Brewer, P.G., Friederich G., Peltzer E.T., Orr Jr. F.M. (1999) Direct experiments on the ocean disposal of fossil fuel CO_2. *Science* 284:943-5

Broecker, W. and Peng, T.H. (1982) *Tracers in the sea*. Lamont-Doherty Geol. Obs., Columbia University, New York, 660 pp.

Buesseler, K.O., Steinberg D.K., Michaels A.F., Johnson R.J., Andrews J.E., Valdes J.R., and Price J.F. (2000) A comparison of the quantity and composition of material caught in a neutrally buoyant versus surface-tethered sediment trap. *Deep-Sea Res II* 47 (2): 277-294.

Cai W. J., Wang Z. H. A., and Wang Y. C. (2003) The role of marsh-dominated heterotrophic continental margins in transport of CO2 between the atmosphere, the land-sea interface and the ocean. *Geophysical Research Letters* 30(16).

Carlson, C.A., H.W. Ducklow and A.F. Michaels (1994). Annual flux of dissolved organic carbon from the euphotic zone in the Northwestern Sargasso Sea. *Nature* 371: 405-408.

Carr, M.E., Tang W.Q., and Liu W.T. (2002) CO_2 exchange coefficients from remotely sensed wind speed measurements: SSM/I versus QuikSCAT in 2000. *Geophys. Res. Lett.* 29 (15): art. no. 1740.

Chavez, F.P., Strutton P.G., Friederich C.E., Feely R.A., Feldman G.C., Foley D.C., and McPhaden M.J. (1999) Biological and chemical response of the equatorial Pacific Ocean to the 1997-98 El Niño. *Science* 286 (5447): 2126-2131.

Coale, K.H., Johnson K.S., Fitzwater S.E., Gordon R.M., Tanner S., et al. (1996) A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. *Nature* 383: 495-501

Codispoti, L. A., J. A. Brandes, J. P. Christensen, A. H. Devol, S. W. A. Naqvi, H. W. Paerl, and T. Yoshinari (2001) The oceanic fixed nitrogen and nitrous oxide budgets: Moving targets as we enter the anthropocene? *Scientia Marina* 65: 85 - 105.

Codispoti, L.A., and Friederich, G.E., (1986) Variability in the inorganic carbon system over the southeastern Bering Sea shelf during the spring of 1980 and spring-summer 1981, *Continental Shelf Research, 5 (1/2),* 133-160.

del Giorgio, P.A., Cole, J.J., Cimbleris, A. (1997). Respiration rates in bacteria exceed phytoplankton production in unproductive aquatic systems. *Nature,* 385, 148-151.

DeGrandpre, M.D., Hammar, T.R., Wallace, D.W.R., Wirick, C.D., (1997) Simultaneous mooring-based measurements of seawater CO_2 and O_2 off Cape Hatteras, North Carolina. *Limnol. Oceanogr., 42,* 21–28.

DeGrandpre, M.D., Olbu, G.J., Beatty, C.M., Hammer, T. R., (2002) Air-sea CO_2 fluxes on the US Middle Atlantic Bight, *Deep-Sea Research II, 49,* 4355-4367.

DeLong, E. F., G. S. Wickham, and N. R. Pace. 1989. Phylogenetic stains: ribosomal RNA-based probes for the identification of single cells. Science 243:1360-3.

Denman K, Hofmann E, Marchant H (1996) Marine biotic responses to environmental change and feedbacks to climate. In: Houghton JT, Meira LG Filho, Callander BA, Harris N, Kattenberg A, Maskell K (eds) *Climate change 1995*. IPCC, Cambridge University Press, 487–516.

Denning, A.S., R.B. Cook, L. Dilling, L Heath, D. McGuire, B. McKee, C. Sabine, R. Oren, K. Paustian, J. Randerson, J. Reilly, S. Running, R. Stallard, M. Torn, and S. Wofsy (2004) Implementation Strategy for the North American Carbon Program. Prepared for the Carbon Cycle Science Steering Group.

Dickey, T., (2003) Emerging ocean observations for interdisciplinary data assimilation systems, *J. Mar. Syst*., 40-41, 5-48.

Dilling, L., S.C. Doney, J. Edmonds, K.R. Gurney, R. Harriss, D. Schimel, B. Stephens, G. Stokes (2003) The role of carbon cycle observations and knowledge in carbon management, *Annual Rev. Environ. Resources,* 28, 18.1-18.38, doi: 10.1146/annurev.energy.28.011503.163443.

Doherty, K.W., D.E. Frye, S.P. Liberatore and J.M. Toole (1999). A moored profiling instrument. *J. Atmos. Oceanic. Tech.* 16: 1816-1829.

Doney, S.C. (1999) Major challenges confronting marine biogeochemical modeling. *Global Biogeochem. Cycles* 13 (3): 705-714.

Doney, S.C., Glover D.M., McCue S.J., and Fuentes M. (2003) Mesoscale variability of Sea-viewing Wide Field-of-view Sensor(SeaWiFS) satellite ocean color: Global patterns and spatial scales. *JGR-Oceans* 108 (C2): art. no. 3024.

Doney, S.C. and M.W. Hecht (2002) Antarctic bottom water formation and deep-water chlorofluorocarbon distributions in a global ocean climate model. *J. Phys. Oceanogr.* 32 (6): 1642-1666.

Doney, S.C. and M. Hood (2002). A Global Ocean Carbon Observation System, A Background Report, Global Ocean Observing System Report No. 118, UNESCO Intergovernmental Oceanographic Commission IOC/INF-1173, 55p

Doney, S.C., K. Lindsay, J.K. Moore, (2003) Global ocean carbon cycle modeling, *Ocean Biogeochemistry*, ed. M. Fasham, Springer, 217-238.

Doney, S.C. and J.L. Sarmiento, ed., (1999). Synthesis and Modeling Project; Ocean biogeochemical response to climate change. U.S. JGOFS Planning Report 22, U.S. JGOFS Planning Office, Woods Hole, MA, 105pp.

Duarte, C.M. and S. Agusti (1998). The CO_2 balance of unproductive aquatic ecosystems. *Science*, 281, 234-236.

Ducklow, H.W., C.A. Carlson, N.R. Bates, A.H. Knap and A.F. Michaels (1995). Dissolved organic carbon as a component of the biological pump in the North Atlantic Ocean. *Phil. Trans. Royal Soc., Series A* 348: 161-167.

Dutay, J.-C., J.L. Bullister, S.C. Doney, J.C. Orr, R. Najjar, K. Caldeira, J.-M. Champin, H. Drange, M. Follows, Y. Gao, N. Gruber, M.W. Hecht, A. Ishida, F. Joos, K. Lindsay, G. Madec, E. Maier-Reimer, J.C. Marshall, R.J. Matear, P. Monfray, G.-K. Plattner, J. Sarmiento, R. Schlitzer, R. Slater, I.J. Totterdell, M.-F. Weirig, Y. Yamanaka, and A. Yool, (2002): Evaluation of ocean model ventilation with CFC-11: comparison of 13 global ocean models. *Ocean Modelling*, ***4***, 89-120.

EDOCC (2001) Ecological Determinants of Oceanic Carbon Cycling: A Framework for Research (http://picasso.oce.orst.edu/ORSOO/EDOCC/), 39pp.

Elser, J.J. and J. Urabe (1999) The stoichiometry of consumer-driven nutrient recycling: Theory, observations, and consequences. *Ecology* 80 (3): 735-751.

Emerson, S., Mecking S., and Abell J. (2001) The biological pump in the subtropical North Pacific Ocean: Nutrient sources, Redfield ratios, and recent changes. *Global Biogeochem. Cycles* 15 (3): 535-554.

Engelen, R.J., Denning, A.S., Gurney, K.R., and Sellers, R.L. (2002) On error estimation in atmospheric CO_2 inversions. *JGR – Atmospheres* 107(D22): art. no. 4635.

Fairall, C.W., J.E. Hare, J.B. Edson, and W. McGillis, (2000) Parameterization and micrometeorological measurement of air-sea gas transfer, *Boundary-Layer Meteorology*, 96, 63-105.

Falkowski, P.G., Barber R.T., and Smetacek V. (1998) Biogeochemical controls and feedbacks on ocean primary production. *Science* 281 (5374): 200-206.

Falkowski, P., Scholes R.J., Boyle E., Canadell J., Canfield D., Elser J., Gruber N., Hibbard K., Hogberg P., Linder S., Mackenzie F.T., Moore B., Pedersen T., Rosenthal Y., Seitzinger S., Smetacek V., and Steffen W. (2000) The global carbon cycle: A test of our knowledge of earth as a system. *Science* 290 (5490): 291-296.

Fan, S., Gloor M., Mahlman J., Pacala S., Sarmiento J., Takahashi T., and Tans P. (1998) A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models. *Science* 282 (5388): 442-446.

Fasham, M.J.R. (ed.) (2003) *Ocean Biogeochemistry*, Springer, Berlin, 297pp.

Fasham, M. J. R., B. M. Balino, M. C. Bowles, R. Anderson, D. Archer, U. Bathmann, P. Boyd, K. Buesseler, P. Burkill, A. Bychkov, C. Carlson, C. T. A. Chen, S. Doney, H. Ducklow, S. Emerson, R. Feely, G. Feldman, V. Garcon, D. Hansell, R. Hanson, P. Harrison, S. Honjo, C. Jeandel, D. Karl, R. Le Borgne and et al. (2001). "A new vision of ocean biogeochemistry after a decade of the Joint Global Ocean Flux Study (JGOFS)." *Ambio* (Special Issue 10): 4-31.

Feely, R.A. and C.L. Sabine (eds.) (2002) A plan for data management of in situ large-scale oceanic carbon observations. NOAA OAR Special Report. (contribution no. 2445 from NOAA/Pacific Marine Environmental Laboratory**).**

Feely, R.A., C.L. Sabine, R.M. Key, and T.-H. Peng (1999): CO_2 survey synthesis results: Estimating the anthropogenic carbon dioxide sink in the Pacific Ocean. U.S. JGOFS News, 9(4), February 1999, 1–4.

Feely, R.A., C.L. Sabine, T. Takahashi, and R. Wanninkhof (2001): Uptake and storage of carbon dioxide in the oceans: The global CO_2 survey. *Oceanography*, 14(4), 18–32.

Feely, R.A., Boutin J., Cosca C.E., Dandonneau Y., Etcheto J., Inoue H.Y., Ishii M., Le Quere C., Mackey D.J., McPhaden M., Metzl N., Poisson A., and Wanninkhof R. (2002) Seasonal and interannual variability of CO_2 in the equatorial Pacific. *Deep Sea Res. II* 49 (13-14): 2443-2469.

Fine, R., L. Merlivat, W. Roether, P. Schlosser, W. Smethie Jr., and R. Wanninkhof (2001) Observing tracers and the carbon cycle, in *Observing the Oceans in the 21st Century*, edited by C.J. Koblinsky, and N.R. Smith, pp. 361-375, GODAE project office Bureau of Meteorology, Melbourne, Australia.

Friedrichs, M. A. M, (2002), Assimilation of JGOFS EqPac and SeaWiFS data into a marine ecosystem model of the central equatorial Pacific Ocean, Deep-Sea Res. II, 49, 289-319,.

Friederich, G.E., Walz P.M., Burczynski M.G., Chavez F.P. (2002). Inorganic carbon in the central California upwelling system during the 1997-1999 El Niño-La Niña event. *Progr. Oceanogr.* 54 (1-4): 185-203.

Fung, I., E. Kalnay, D. Schimel, S. Denning, S. Doney, S. Pawson, A US Carbon Data Assimilation Program Workshop Report, http://dataportal.ucar.edu/CDAS/workshops.html, 20pp.

Gibson G. 2002. Microarrays in ecology and evolution: a preview. Molecular Ecology **11:** 17-24.

Giovannoni, S. J., T. B. Britschgi, C. L. Moyer, and K. G. Field. 1990. Genetic diversity in Sargasso Sea bacterioplankton. Nature **345:** 60-63.

Glen, S. and T. Dickey, eds. (2002) Scientific Cabled Observatories for Time Series (SCOTS) Report. Draft manuscript, 90pp.

Gloor, M, Fan SM, Pacala S, Sarmiento J, Ramonet M. (1999) A model-based evaluation of inversions of atmospheric transport, using annual mean mixing ratios, as a tool to monitor fluxes of nonreactive trace substances like CO_2 on a continental scale. *JGR-Atmospheres* 104 (D12): 14245-14260.

Gloor, M., N. Gruber, J.L. Sarmiento, C.L. Sabine, R.A. Feely, and C. Rödenbeck (2003): A first estimate of present and preindustrial air-sea CO2 flux patterns based on ocean interior carbon measurements and models. Geophys. Res. Lett., 30(1), 1010, doi:10.1029/2002GL015594.

Glover, D.M., N.M. Frew, S.J. McCue, and E.J. Bock, 2002, A multi-year time series of global gas transfer velocity from the TOPEX dual frequency, normalized radar backscatter algorithm, in Gas Transfer at Water Surfaces}, M. Donelan, W. Drennan, E. Saltzman, and R. Wanninkhof (eds), Geophysical Monograph 127, American Geophysical Union, Washington, DC, 325-331.

Glover, D. M., S. C. Doney, A. J. Mariano, R. H. Evans, and S. J. McCue, (2002) Mesoscale variability in time series data: Satellite estimates for the U.S. JGOFS Bermuda Atlantic Time-Series Study (BATS) site, J. Geophys. Res., 107 (C8), 7-1 to 7-21.

Glover, D.M, K. Buesseler, C. Chandler, S.C. Doney, and G. Heimerdinger, (2003) The U.S. JGOFS data management experience, *in prep.*

Gruber, N. (1998): Anthropogenic CO_2 in the Atlantic Ocean. *Global Biogeochem. Cycles*, 10, 809-837.

Gruber, N., J.L. Sarmiento and T.F. Stocker (1996) An improved method for detecting anthropogenic CO_2 in the oceans. *Global Biogeochem. Cycles*, 10, 809-837.

Gruber, N., Keeling C.D., and Bates N.R. (2002) Interannual variability in the North Atlantic Ocean carbon sink. *Science* 298 (5602): 2374-2378.

Gurney KR, Law RM, Denning AS, Rayner PJ, Baker D, Bousquet P, Bruhwiler L, Chen YH, Ciais P, Fan S, Fung IY, Gloor M, Heimann M, Higuchi K, John J, Maki T, Maksyutov S, Masarie K, Peylin P, Prather M, Pak BC, Randerson J, Sarmiento J, Taguchi S, Takahashi T, Yuen CW (2002) Towards robust regional estimates of CO2 sources and sinks using atmospheric transport models, Nature, 415, 626-630.

Gust, G. and Kozerski H.P. (2000) In situ sinking-particle flux from collection rates of cylindrical traps. *Mar. Ecol.-Prog. Ser.* 208: 93-106.

Hall A. and Visbeck M. (2002) Synchronous variability in the southern hemisphere atmosphere, sea ice, and ocean resulting from the annular mode. *J Climate* 15 (21): 3043-3057.

Hansell, D.A. and C.A. Carlson (1998). Deep ocean gradients in dissolved organic carbon concentrations. *Nature* **395**: 263-266.

Hansell, D.A. and C.A. Carlson (2001) Biogeochemistry of total organic carbon and nitrogen in the Sargasso Sea: Control by convective overturn. *Deep Sea Res. II* 48: 1649-1667.

Harris, R.P. (1994) Zooplankton Grazing on the coccolithophore Emiliani huxlei and its role in inorganic carbon flux. *Mar. Biol.* 119: 431-439.

Hedges, J.I., J.A. Baldock, Y. Gélinas, C. Lee, M. Peterson and S.G. Wakeham (2001) Evidence for non-selective preservation of organic matter in sinking marine particles. *Nature* 409: 801-804.

Heimann, M., and E. Maier-Reimer (1996): On the relations between the oceanic uptake of CO_2 and its carbon isotopes. *Global Biogeochem. Cycles*, 10(1), 89–110.

Hoge, F. E., P. E. Lyon, R. N. Swift, J. K. Yungel, M. R. Abbott, R. M. Letelier, and W. E. Esaias, (2003), Validation of Terra-MODIS phytoplankton chlorophyll fluorescence line height. I. Initial airborne lidar results, Appl. Opt., 42(15), 2767-2771.

Hood, E.M., Merlivat L. and Johannessen T. (1999) Variations of $f\mathrm{CO}_2$ and air-sea flux of CO_2 in the Greenland Sea gyre using high-frequency time series data from CARIOCA drift buoys. *JGR-Oceans* 104 (C9): 20571-20583.

Hood, E.M. and Merlivat L. (2001a) Annual to interannual variations of $f\mathrm{CO}_2$ in the northwestern Mediterranean Sea: Results from hourly measurements made by CARIOCA buoys, 1995-1997. *J. Mar. Res.* 59 (1): 113-131.

Hood, E.M., Wanninkhof R. and Merlivat L. (2001b) Short timescale variations of $f(CO_2)$ in a North Atlantic warm-core eddy: Results from the Gas-Ex 98 carbon interface ocean atmosphere (CARIOCA) buoy data. *JGR-Oceans* 106 (C2): 2561-2572.

Hooker, S. B., and C. R. McClain, The calibration and validation of SeaWiFS data, Prog. Oceanogr., 45, 427-465, 2000.

Houghton, Meira Filho, Callander, Harris Kattenberg and Maskell (eds) (1995), Climate Change (1995) The Science of climate change. Contribution of Working Group I to the second assessment report of the IPCC. Cambridge University Press, Cambridge, UK, 572pp.

Jahnke, R.A. (1996) The global ocean flux of particulate organic carbon: areal distribution and magnitude. *Global Biogeochem. Cycles*, 10, 71 - 88.

Johnson, K.S., C. Reimers, and M. DeGrandpre (2000). In situ chemical analysis. In: Future of Ocean Chemistry in the U.S., edited by L. Mayer and E. Druffel. University Corporation for Atmospheric Research, Boulder, 89–95.

Joos, F., Plattner G.K., Stocker T.F., Marchal O. and Schmittner A. (1999) Global warming and marine carbon cycle feedbacks an future atmospheric CO_2. *Science* 284 (5413): 464-467.

Karl, D.M. (1999) A sea of change: Biogeochemical variability in the North Pacific Subtropical Gyre. *Ecosystems* 2 (3): 181-214.

Karl, D.M., E.A. Laws, P. Morris, P.J.L. Williams, S. Emerson (2003) Global carbon cycle - Metabolic balance of the open sea, *Nature*, 426, 32.

Keeling, R.F. and S.R. Shertz (1992): Seasonal to interannual variations in atmospheric oxygen and implications for the global carbon cycle. *Nature*, 358, 723-727.

Keeling, R.F., S.C. Piper and M. Heimann (1996): Global and hemispheric CO_2 sinks deduced from changes in atmospheric O_2 concentration. *Nature*, 381, 218-221.

Keeling, R.F., B.B. Stephens, R.G. Najjar, S.C. Doney, D. Archer, M. Heimann, 1998: Seasonal variations in the atmospheric O_2/N_2 ratio in relation to the kinetics of air-sea gas exchange, *Global Biogeochem. Cycles*, **12**, 141--163.

Kleypas, J.A., Buddemeier R.W, Archer D., Gattuso J.-P., Langdon C., Opdyke B.N. (1999) Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science* 284 (5411): 118-120.

Lapitan, R.L., R. Wanninkhof, and A.R. Mosier (1999) Methods for stable gas flux determination in aquatic and terrestrial systems. In *Scaling of Trace Gas Fluxes between Terrestrial and Aquatic Ecosystems and the Atmosphere*, A.F. Bouwman (ed.), Elsevier, Amsterdam, 27–66.

Le Quéré, C., Orr J.C., Monfray P., Aumont O. and Madec G. (2000) Interannual variability of the oceanic sink of CO_2 from 1979 through 1997. *Global Biogeochem. Cycles* 14 (4): 1247-1265.

Le Quéré, C., Bopp L. and Tegen I. (2002) Antarctic circumpolar wave impact on marine biology: A natural laboratory for climate change study. *Geophys. Res. Lett.* 29 (10): art. no. 1407.

Le Quéré, C., O. Aumont, L. Bopp, P. Bousquet, P. Ciais, R. Francy, M. Heinman, C. D. Keeling, H. Kheshgi, P. Peylin, S. C. Piper, I. C. Prentice, and P. J. Rayner, Two decades of oceanic CO2 sink and variability, *Tellus, 55 (2):* 649-656, 2003.

Lee, C., M. Abbott, R. Anderson, J. Barth, M. Bender, S. Doney, H. Ducklow, R. Feely, D. Hansell, D. Karl (2000) Ocean Carbon Transport, Exchanges and Transformations (http://www.msrc.sunysb.edu/octet/).

Lee, C., S.G. Wakeham and J.I. Hedges (2000). Composition and flux of particulate amino acids and chloropigments in equatorial Pacific seawater and sediments. *Deep Sea Res. I* 47: 1535-1568.

Lindstrom, E., ed. (2000) Ocean Theme for the IGOS Partnership, a report from the Ocean Theme Team, NASA Headquarters, Washington, D.C., USA.

Liss, P.S. and L. Merlivat (1986) Air-sea gas exchange rates: introduction and synthesis. In The Role of Air-Sea Exchange in Geochemical Cycling, P. Buat-Menard, ed., Reidel, Dordrecht, 113-127.

MacKenzie, F.T. (1981). Global carbon cycle: Some minor sinks for CO_2. *Flux of Organic Carbon by Rivers to the Ocean.* G. E. Likens, F.T. MacKenzie, J. E. Richey, J. R. Sedell and K. K. Turekian. Washington DC, U.S. Dept. of Energy**:** 360-384.

Mahoney, J.R. (ed.) (2003) Strategic plan for the U.S. Climate Change Program, Climate Change Science Program Office, Washington, D.C., 202 pp.

Martin, J.H., G.A. Knauer, D.M. Karl and W.W. Broenkow (1987). VERTEX: carbon cycling in the notheast Pacific. *Deep Sea Res. II* 34: 267-285.

Matear, R.J. and A.C. Hirst (1999): Climate change feedback on the future oceanic CO_2 uptake, *Tellus, Ser. B.*, 51, 722–733.

Matear, R.J., A.C. Hirst and B.I. McNeil, 2000: Changes in dissolved oxygen in the Southern Ocean with climate change. Geochem. Geophys. Geosystems, 1, November 21, http://g-cubed.org/.

McClain, C. R., S.-Y. Chao, L. P. Atkinson, J. O. Blanton and F. de Castillejo, (1986), Wind-driven upwelling in the vicinity of Cape Finisterre, Spain, J. Geophys. Res., 91(C7), 8470-8486.

McClain, C.R., Cleave M.L., Feldman G.C., Gregg W.W., Hooker S.B. and Kuring N. (1998) Science quality SeaWiFS data for global biosphere research. *Sea Technology* 39(9): 10-16.

McClain, C. R., L. J. Pietrafesa, and J. A. Yoder, (1984), Observations of Gulf Stream-induced and wind-driven upwelling in the Georgia Bight using ocean color and infrared imagery, J. Geophys. Res., 89(C3), 3705-3723.

McClain, C. R., J. Ishizaka and E. Hofmann, (1990), Estimation of phytoplankton pigment changes on the Southeastern U. S. continental shelf from a sequence of CZCS images and a coupled physical-biological model, J. Geophys. Res., 95(C11), 20213-20235.

McClain, C. R. and 24 others, (2002a), Science and Observation Recommendations for Future NASA Carbon Cycle Research, NASA/TM-2002-210009, NASA Goddard Space Flight Center, Greenbelt, Maryland, 171 pp.

McClain, C. R., S. Signorini, J. Christian, M. Lewis, I. Asunuma, D. Turk, and C. Dupouy-Douchement, (2002b), Satellite ocean color observations of the tropical Pacific Ocean, Deep-Sea Res. II, 49, 2533-2560.

McGillis, W.R., Edson J.B., Hare J.E., Fairall C.W. (2001a) Direct covariance air-sea CO_2 fluxes. *JGR-Oceans* 106 (C8): 16729-16745.

McGillis, W.R., Edson J.B., Ware J.D., Dacey J.W.H., Hare J.E., Fairall C.W. and Wanninkhof R. (2001b) Carbon dioxide flux techniques performed during GasEx-98. *Mar. Chemistry* 75 (4): 267-280.

McKee, B., (ed.) (2003) *The transport, transformation, and fate of carbon in river-dominated ocean margins*, Community Workshop Report, http://www.tulane.edu/~riomar.

McKinley GA, Follows MJ, Marshall J (2000) Interannual variability of the air-sea flux of oxygen in the North Atlantic, Geophys. Res. Lett., 27, 2933-2936.

Michaels, A.F. and M.W. Silver (1988). Primary production, sinking fluxes and the microbial food web. *Deep Sea Res. II* 35(4): 473-490.

Millero, F.J., Hiscock, W.T., Huang, F., Roche, M., Zhang, J-Z., 2001.Seasonal variation of the carbonate system in Florida Bay, *Bull. Mar. Sci., 68(1),* 101-123.

Moore, J.K., S.C. Doney, J.A. Kleypas, D.M. Glover, and I.Y. Fung (2002a) An intermediate complexity marine ecosystem model for the global domain.*Deep-Sea Res., II*, **49**, 403-462.

Moore, J.K., S.C. Doney, D.M. Glover, and I.Y. Fung (2002b) Iron cycling and nutrient limitation patterns in surface waters of the world ocean. *Deep-Sea Res., II*, **49**, 463-507.

Moran, M. A., J. M. Gonzalez, and R. P. Kiene. 2003. Linking a bacterial taxon to sulfur cycling in the sea: Studies of teh marine Roseobacter group. Geomicorbiology Journal **204:** 375-388.

Murtugudde, R. G., S. R. Signorini, J. R. Christian, A. J. Busalacchi, and C. R. McClain, (1999), Ocean color variability of the tropical Indo-Pacific basin observed by SeaWiFS during 1997-98, J. Geophys. Res., 104(C8), 18,351-18,366.

National Research Council (NRC), (2002), Chemical Reference Materials: Setting the Standards for Ocean Science, Washington, D.C., National Academy Press, 130 pp.

Najjar, R.G. and Keeling R.F. (2000) Mean annual cycle of the air-sea oxygen flux: A global view. Global Biogeochem. Cycl., 14 (2): 573-584.

Nightingale, P.D., Malin G., Law C.S., Watson A.J., Liss P.S., Liddicoat M.I., Boutin J. and Upstill-Goddard R.C. (2000) In situ evaluation of air-sea gas exchange parameterizations using novel conservative and volatile tracers. *Global Biogeochem. Cycles* 14 (1): 373-387.

Park, P.K., Gordon, L.I., Alvrez-Borrego, S., 1974. The carbon dioxide system of the Bering Sea, *in Oceanography of the Bering Sea*, D.W. Hood and E. J. editors, Occasional Publication No. 2, Institute of Marine Science, University of Alaska, Fairbanks, AK.

Pearson, P.N. and Palmer M.R. (2000) Atmospheric carbon dioxide concentrations over the past 60 million years. *Nature* 406 (6797): 695-699.

Peinert, R., B. v. Bodungen and V.S. Smetacek (1989). Foodweb structure and loss rate. *Productivity of the Ocean: Present and Past*. W.H. Berger, V.S. Smetacek and G. Wefer. S. Bernhard, Dahlem Konfernzen, John Wiley and Sons Limited**:** 35-48

Peng, T.-H. R. Wanninkhof, J.L. Bullister, R.A. Feely and T. Takahashi (1999): Quantification of decadal anthropogenic CO_2 uptake in the ocean based on dissolved inorganic carbon measurements. *Nature*, 396, 560-563.

Ploug, H. and H. P. Grossart (1999) Bacterial production and respiration in suspended aggregates- a matter of the incubation method, *Aquat. Microb. Ecol.* 20: 21-29

Prentice, C. et al. (2001): The carbon cycle and atmospheric carbon dioxide, in *Climate Change 2001: The scientific basis,* Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, J. Houghton et al., (Editors). Cambridge University Press, New York, NY, USA.

Quay, P.D., B. Tilbrook, and C.S. Wong (1992): Oceanic uptake of fossil fuel CO_2: Carbon-13 evidence, *Science*, 256, 74–79.

Quay, P.D., R. Sonnerup, T. Westby, J. Stutsman and A. McNichol. (2003). Anthropogenic changes of the 13C/12C of dissolved inorganic carbon in the ocean as a tracer of CO_2 uptake. *Global Biogeochem. Cycles.*

Redfield, A.C. (1948) The exchange of oxygen across the sea surface, *J. Mar. Res.*, 7, 347-361.

Riebesell, U., Zondervan I., Rost B., Tortell P.D., Zeebe R.E., Morel F.M.M. (2000) Reduced calcification of marine plankton in response to increased atmospheric CO_2. *Nature* 407 (6802): 364-367.

Roemmich, D., Boebel, O., Desaubies, Y., Freeland, H., King, B., LeTraon, P.-Y., Molinari, B., Owens, B., Riser, S., Send, U., Takeuchi, K., Wijffels, S., 1999. Argo: the global array of profiling floats. The Ocean Observing System for Climate, International Symposium, Saint Raphael, France.

Sabine, C.L., R.M. Key, K.M. Johnson, F.J. Millero, A. Poisson, J.L. Sarmiento, D.W.R. Wallace, and C.D. Winn (1999): Anthropogenic CO_2 Inventory in the Indian Ocean, *Global Biogeochem. Cycles,* 13, 179-198.

Sabine, C.L., R.A. Feely, R.M. Key, J.L. Bullister, F.J. Millero, K. Lee, T.-H. Peng, B. Tilbrook, T. Ono, and C.S. Wong (2002): Distribution of anthropogenic CO_2 in the Pacific Ocean. *Global Biogeochem. Cycles*, 16(4), 1083, 10.1029/2001GB001639.

Sambrotto, R.N., G. Savidge, C. Robinson, P. Boyd, T. Takahashi, D.M. Karl, C. Langdon, D. Chipman, J. Marra, and L. Codispoti (1993). Elevated consumption of carbon relative to nitrogen in the surface ocean. *Nature* 363: 248-250.

Sarmiento J.L., Gruber N. (2002) Sinks for anthropogenic carbon. *Physics Today* 55 (8): 30-36.

Sarmiento, J.L. and S.C. Wofsy (co-chairs). (1999) A U.S. Carbon Cycle Science Plan, Report of the Carbon and Climate Working Group, prepared for the agencies of the U.S. Global Change Research Program, 69 pp.

Sarmiento J.L., Monfray P, Maier-Reimer E, Aumont O, Murnane RJ, and Orr JC. (2001) Sea-air CO_2 fluxes and carbon transport: A comparison of three ocean general circulation models. *Global Biogeochem. Cycles* 14 (4): 1267-1281.

Sarmiento, J.L., T.M.C. Hughes, R.J. Stoufer, and S. Manabe (1998): Simulated response of the ocean carbon cycle to anthropogenic climate warming, *Nature*, 393, 245–249.

Schlitzer, R. (2000) Applying the adjoint method for biogeochemical modeling: export of particulate organic matter in the world ocean, in *Inverse Methods in Global Biogeochemical Cycles*, Geophysical Monograph, 114, AGU, pp. 107 - 124.

Seitzinger, S. and D. Kroeze (1998) Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems. *Global Biogeochem. Cycles* 12:93-113.

Siedler, G., J. Church, and J. Gould (ed.) (2001) *Ocean Circulation and Climate*, Academic Press, New York, 714pp.

Siegenthaler U. and J.L. Sarmiento (1993) Atmospheric carbon dioxide and the ocean. *Nature* 365:119–125

Simpson, J.J., 1985. Air-sea exchange of carbon dioxide and oxygen induced by phytoplankton: Methods and interpretation, in Mapping Strategies in Chemical Oceanography, A. Zirino, dditor, American Chemical Society, Washington, D.C., 409 – 450.

Stanley, R.H.R., K.O. Buesseler, S.J. Manganini, D.K. Steinberg, and J.R. Valdes (2003). A comparison of major and minor elemental fluxes collected using neutrally buoyant and surface-tethered traps, submitted to *Deep-Sea Res. I*.

Takahashi, T., Olafsson J., Goddard J.G., Chipman D.W., and Sutherland S.C. (1993) seasonal-variation of CO_2 and nutrients in the high-latitude surface oceans - a comparative-study. *Global Biogeochem. Cycles* 7 (4): 843-878.

Takahashi, T., Feely R.A., Weiss R.F., Wanninkhof R.H., Chipman D.W., Sutherland S.C., and Takahashi T.T. (1997) Global air-sea flux of CO_2: An estimate based on measurements of sea-air pCO_2 difference. *Proc. Nat. Acad. Sci., USA* 94 (16): 8292-8299.

Takahashi, T., Wanninkhof, R.T., Feely, R.A., Weiss, R.F., Chipman, D.W., Bates, N.R., Olafsson J., Sabine, C.L., and Sutherland, C.S. (1999). Net sea-air CO_2 flux over the global ocean: an improved estimate based on air-sea pCO_2 difference. In *Proceeding of the 2nd Symposium on CO_2 in the oceans* (Nojiri, Y. ed.). pp 9-15 Tsukuba, Japan.

Takahashi, T., Sutherland S.C., Sweeney C., Poisson A., Metzl N., Tilbrook B., Bates N., Wanninkhof R., Feely R.A., Sabine C., Olafsson J., and Nojiri Y. (2002) Global sea-air CO2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects. *Deep-Sea Res. II* 49 (9-10): 1601-1622.

Tans, P. P., J. A. Berry, and R. F. Keeling (1993): Oceanic $^{12}C/^{13}C$ observations: a new window on ocean CO_2 uptake, *Global Biogeochem. Cycles*, 7(2), 353–368.

Thompson, D.W.J. and Wallace J.M. (2000) Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate* 13 (5): 1000-1016

Tsunogai, S., S. Watanabe, and T. Sato (1999): Is there a continental shelf pump for the absorption of atmospheric CO_2? *Tellus*, 51B, 701–712.

Turk, D., M. J. McPhaden, A. J. Busalacchi, and M. R. Lewis, (2001), Remotely sensed biological production in the equatorial Pacific, *Science*, 293, 471-474.

van Geen, A., Takesue, R.K., Goddard, J., Takahashi, T., Barth, J.A. Smith, R.L. 2000. Carbon and nutrient dynamics during coastal upwelling off Cape Blanco, Oregon. Deep-sea Research II, 47: 975-1002.

Vlahos, P., Chen, R.F., and D.J. Repeta (2002); Dissolved organic carbon in the Mid-Atlantic Bight, *Deep-Sea Res. II*, 49, 4369 – 4385.

Volk, T. and M. I. Hoffert (1985). Ocean carbon pumps: Analysis of relative strengths and efficiencies in ocean-driven atmospheric CO2 change. In: *The Carbon Cycle and Atmospheric CO2, Natural Variations Archean to Present*. Geophysical Monograph Series, vol. 32, eds. E. T. Sundquist and W. S. Broecker, pp. 99-110, AGU, Washington, D.C.

Wallace, D.W.R. (2001) Introduction to special section: Ocean measurements and models of carbon sources and sinks. *Global Biogeochem. Cycles* 15 (1): 3-10.

Wanninkhof, R. (1992) Relationship between wind-speed and gas-exchange over the ocean. *JGR-Oceans* 97 (C5): 7373-7382.

Wanninkhof, R. and W.R. McGillis (1999) A cubic relationship between air-sea CO_2 exchange and wind speed. *Geophys. Res. Lett.* 26 (13): 1889-1892

Wanninkhof, R., S.C. Doney, T.-H. Peng, J.L. Bullister, K. Lee, and R.A. Feely (1999): Comparison of methods to determine the anthropogenic CO_2 invasion into the Atlantic Ocean. *Tellus*, 51B, 511–530.

Watson, A.J., Upstill-Goddard R.C. and P.S. Liss (1991) Air- sea gas exchange in rough and stormy seas measured by a dual- tracer technique. *Nature* 349, 145-147.

White, W.B. and Peterson R.G. (1996) An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent. *Nature* 380 (6576): 699-702.

Williams, R.G., A. McLaren, and M.J. Follows (2000) Estimating the convective supply of nitrate and implied variability in export production, Global Biogeochem. Cycle, 14, 1299-1313.

Wofsy, S.C. and R.C. Harriss (2002) *The North American Carbon Program Plan (NACP).* Report of the NACP Committee of the U.S. Interagency Carbon Cycle Science Program, Washington, DC: US Global Change Research Program.

Yoder, J. A., S. G. Ackleson, R. T. Barber, P. Flament, and W. M. Balch, (1994), A line in the sea, *Nature*, 371, 689-692.

Yool, A. and Fasham M.J.R. (2001) An examination of the "continental shelf pump" in an open ocean general circulation model. *Global Biogeochem. Cycles* 15 (4): 831-844.

Yuan, X.J. and Martinson D.G. 2001 The Antarctic Dipole and its predictability. *Geophys. Res. Lett.* 28 (18): 3609-3612.

Zappa, C.J., W.E. Asher, A.T. Jessup, J. Klinke, and S.R. Long (2002) Effect of microscale wave breaking on air-water gas transfer, in *Gas Transfer at Water Surfaces*, edited by M. Donelan, W. Drennan, E. Saltzman, and R. Wanninkhof, pp. 23-31, AGU, Geophysical Monograph 127, Washington, DC.

Zehr, J. P., B. D. Jenkins, S. M. Short, and G. F. Steward. 2003. Nitrogenase gene diversity and microbial community structure: a cross-system comparison. Environmental Microbiology **5:** 539-554