OMELET: An Integrated Carbon Cycle Research Plan for the Ocean Sciences

Concentrations of CO_2 in the atmosphere have been rising since the onset of the industrial revolution due to the combustion of fossil fuels and land-use practices. From a preindustrial modern level of ~280 ppm, atmospheric CO_2 has now risen to ~370 ppm. This recent anthropogenic increase in atmospheric CO_2 now exceeds the full amplitude (~80 ppm) of the natural change in atmospheric CO_2 associated with the major glacial-interglacial cycles of the past few hundred thousand years. Current projections suggest that concentrations of atmospheric CO_2 may exceed 700 ppm within the next 100 years. Levels this high have not been experienced on Earth for the past million years, and probably longer, back to the early Cenozoic (prior to ~50 Ma). This was a time when earth's climate was much warmer than today, as evidenced by the absence of polar ice caps at that time.

Carbon dioxide is a greenhouse gas with well-known physical properties that enable it to trap outgoing long-wave radiation. However, just as the role of atmospheric CO_2 in regulating past changes in earth's climate remains a topic of intense investigation, the climatic response to future emissions of anthropogenic CO_2 remains to be established as well. Uncertainties exist both because multiple factors influence earth's energy budget, which drives climate change, and because the fraction of anthropogenic CO_2 that will remain in the atmosphere is sensitive to perturbations of the natural carbon cycle, which may result from global warming. While CO_2 is the principal greenhouse gas influenced significantly by human activities, other factors will have a major impact on climate change, including, for example, trends in the concentration of other greenhouse gases (e.g., CH_4), as well as the concentrations, distributions, and optical properties of anthropogenic aerosols. Ocean biogeochemistry will also respond to other aspects of global change beyond climate (e.g., nutrient eutrophication; atmospheric iron deposition). Reliable predictions of future climate change will depend not only on models that accurately depict the complex interactions among multiple factors forcing earth's climate system, but also on an accurate understanding of the feedbacks within the terrestrial and ocean carbon cycles that will affect future trajectories of atmospheric CO_2.

Of the CO_2 released by fossil fuel combustion and deforestation to the atmosphere, about one third remains in the atmosphere, a similar amount accumulates in the terrestrial biosphere, and the remaining third is taken up by the ocean. Future climate scenarios will depend on whether this partitioning of anthropogenic CO_2 is maintained, or whether feedbacks resulting from perturbations of the marine and terrestrial carbon cycles will lead to an increase or a decrease in the fraction of anthropogenic CO_2 remaining in the atmosphere.

While our understanding of the oceanic C cycle has improved dramatically in the last decade, we cannot yet predict probable ocean responses to global change. Similarly we have not yet developed the capability to address the physical, chemical and biological feedbacks to atmospheric CO_2. A quantitative understanding of the ocean carbon cycle is a necessary but certainly not a sufficient condition for addressing these issues. Credible projections of the ocean carbon cycle response to climate perturbation will not be possible without a much more detailed, mechanistic understanding of the processes controlling the partitioning of carbon among the marine, terrestrial and atmospheric reservoirs. One of the critical components needed to answer these questions is an improved understanding of the past, present and future variability of the ocean carbon cycle especially as it relates to the air-sea and land-sea exchange of carbon.

The Carbon Cycle Science Plan (CCSP) prepared for the U.S. Global Change Research Program has outlined a strategic mix of terrestrial, oceanic and atmospheric research dedicated to answering two fundamental questions: What has happened to the carbon dioxide that has been emitted by human activities? How will the atmospheric carbon dioxide concentration evolve in the future? The CCSP identified several key areas to pursue in advancing our understanding of the ocean carbon sink: constraining interannual variability of air-sea CO_2 flux and its spatial distribution, determining changes in anthropogenic CO_2 inventory distribution, and determining the sensitivity of air-sea CO_2 fluxes and CO_2 storage to changes in climate. To accomplish these tasks will require a research plan that combines CO_2 measurement surveys, process studies that identify and quantify mechanisms that drive carbon transfer, and transport models that simulate anthropogenic CO_2 uptake within the framework of a biological carbon cycle. *Thus, the oceanographic community sees the urgent need to improve our understanding of, and ability to quantitatively describe, the physical, biological and chemical mechanisms controlling* CO_2 *fluxes and transformations of ocean carbon.*

Several recent workshops have engaged in an effort to identify specific research objectives that would improve our understanding of carbon dynamics in the ocean. Strikingly, several themes were common among these groups (OCTET: Ocean Carbon Transport, Exchanges and Transformation; EDOCC: Ecological Determinants of the Ocean Carbon Cycle; SOLAS: Surface Ocean Lower Atmosphere Study; US-JGOFS SMP Continental Margins Workshop). These include:

- What are the critical components of the ocean C cycle regulating the partitioning of CO_2 between the atmosphere and the ocean, and how can we improve prediction of the response of these processes to changes in environmental conditions (e.g., due to global warming)?

- What are the potential responses of marine ecosystems and ocean biogeochemical cycles to climate?

- How do we adequately characterize the non-steady state behavior of oceanic systems? How do components of the ocean system - physical and ecological - move between semi-stable states? What are the stabilizing (negative) and destabilizing (positive) feedbacks inherent in the system?

- How can we more realistically represent biological, physical and chemical processes in ocean carbon cycle models?

Implementation of any research effort that addresses ocean C cycling in a global context will require an integrated earth systems approach that incorporates various disciplines and international partners. Tracking changes in organic and inorganic carbon pools in the ocean involves a better understanding of ecosystem dynamics, interlinking biogeochemical cycles, and oceanic physical circulation. Understanding the supply of trace nutrients at ocean boundaries (the sea surface and continental margins) requires an extension of studies from the oceanic realm to the lower atmosphere and to the continents, including hydrological effects. Processes in the open ocean and along continental margins such as upwelling, remineralization, denitrification, sedimentation, etc., are likely to experience changes that impact oceanic carbon and nutrient cycling rates as wind regimes and ocean circulation change under variable climate conditions. Integration of such a wealth of information will be a formidable task, but it is envisioned that developing a cohesive ocean C program within the framework of the CCSP will act as a first step in such an effort. Discussion of the ocean carbon cycle must therefore be wide-ranging and include the effects of, for example, continental and aeolian input of trace nutrients such as iron, climatic impacts on circulation, ecosystem regime shifts, etc. We need to maintain a broad research scope because the earth's carbon cycle has many possible feedback loops.

The above leads us to pose the following overarching questions:

- **How will the oceanic carbon cycle respond to future climate forcing and other global changes?**

- **Will these oceanic carbon cycle responses accelerate (or decelerate) such future global changes (e.g., the build-up of CO_2 in the atmosphere)?**

Research Approach

The ocean carbon cycle is dominated by two interdependent carbon pumps that can both affect depletion of total CO_2 in surface relative to deep water. Because the solubility of CO_2 in seawater increases with decreasing temperature, the **solubility pump** transfers CO_2 to the deep sea as the formation of cold deep waters at high latitudes acts as a temperature-dependent sink for atmospheric CO_2. The **biological pump** removes carbon from surface waters by gravitational settling, diffusion, and active biotransport of organic (the "soft tissue pump") and inorganic carbon (the "carbonate pump") derived from biological production. Even though both biological pumps have the net effect of removing carbon from surface waters, their effects on the partitioning of CO_2 between the atmosphere and the ocean are different. While the carbonate or hard tissue pump decreases the ability of the upper ocean to absorb atmospheric CO_2, the soft tissue pump has the opposite effect. An increased effort is clearly needed to understand the influence of climate on the processes controlling these carbon pumps, as well as potential feedbacks on the climate system via air-sea carbon exchange.

Perturbations of the solubility pump arise through changes in seawater temperature and circulation, so it is inevitable that global warming will alter the solubility-driven storage of carbon in the ocean. We have a basic understanding of how physical forcing affects the solubility pump. The processes needing further research include those that affect physical forcing and that cause temporal and spatial variation. Inventory and transport observations are essential to the investigation of the large-scale solubility pump. Repeated oceanic sampling of carbon system parameters, tracers of ocean circulation and hydrography is critical to determining DIC transport and inventory changes. It is necessary to: (1) quantify changes in the rates and spatial patterns of oceanic carbon uptake, fluxes and storage of anthropogenic CO_2, (2) detect and quantify changes in water mass renewal and mixing rates, and (3) provide a validation of the time integration of models of natural and anthropogenic climate variability. One strategy is to put in place a global ocean-observing network for CO_2 and tracers to document the continuing large-scale evolution of these fields.

In addition several surface solubility pump processes operate on shorter time scales. We need to better estimate the present-day exchange between the atmosphere and the surface ocean of CO_2 and other substances that affect the ocean carbon cycle, and determine which surface layer processes play a large role in regulating interannual variability of air-sea CO_2 flux. This interannual variability must be constrained quantitatively to provide reliable estimates of the location and magnitude of northern hemisphere carbon sinks.

The biological pump transports to deeper water the organic carbon and $CaCO_3$ produced by organisms in the surface ocean. In deeper waters, this fixed carbon is largely dissolved as DOC or remineralized to CO_2, adding to the total C reservoir that is isolated from the atmosphere. There are only a few basic mechanisms by which changes in the ocean's biological pump can alter the partitioning of CO_2 between the ocean and the atmosphere: (1) a change in the inventory, supply or uptake efficiency of limiting nutrients; (2) changes in stoichiometric ratios of organic matter produced and retained in the surface layer, or exported from it; (3) changes in the form of organic carbon produced and exported biologically (with consequent changes in the depth scales of remineralization for C, N and P), and (4) changes in the organic carbon/$CaCO_3$ ratio of biogenic debris sinking through the water column.

The structure of oceanic food webs affects the biological pump by influencing the quality and quantity of carbon export from particular ecosystems, as well as elemental ratios of its biota and dissolved nutrient pools. Food web structures vary in space and in time over seasonal, annual, decadal and geologic time scales. Elemental stoichiometries, the ratios of one element to another in either the particulate or dissolved phase, are often key factors in geochemical models. They are emergent properties of marine ecosystems, dictated by the differential partitioning of elements as they flow through the food web. We do not fully understand what constrains these ratios, but do know that results of geochemical models can be very sensitive to assumptions about these stoichiometries. Characterization of the biological pump and food web structure requires two distinctive but interrelated approaches in the study of the role of oceanic biology in elemental cycles. A “process-functional” approach studies the flows of energy and material in ecological systems, and a “population-community” approach studies the dynamics of population interactions and the patterns of trophic connections. Both approaches are needed if the objectives are to acquire a mechanistic understanding of the ocean’s response to changing climate and the role of the ocean in carbon sequestration.

Globally, at steady-state, the physical supply of inorganic carbon essentially balances the biological export of organic carbon and $CaCO_3$ from the surface ocean. If climate change produces an imbalance between physical supply and biological export, then the CO_2 concentration in the surface ocean will change. Two specific questions that must be answered: (1) How will climate change affect the biological transfer of organic carbon out of the surface ocean? (2) How will climate change affect the transfer of dissolved inorganic carbon to the surface ocean? The answer to the first question centers around the changes in the carbon transferred by the “biological pump” including both the production of organic carbon in the photic layer and remineralization of organic carbon in the deeper layers. The answer to the second question centers on both changes in the rates of circulation and mixing, and changes in the “solubility pump” which depend on changes in surface temperatures as well as circulation. Fundamentally, this link between physics and biology implies that an answer to how climate impacts the ocean carbon cycle must include determinations of the change in the physical circulation/mixing rates and biological production/remineralization rates of carbon.

Determining how the response of the ocean carbon cycle to climate change will feed back on that change requires us to resolve anthropogenic effects from natural variability, and to accurately parameterize natural processes in ocean carbon cycle models. To address the first issue we need to plan our field measurements over appropriate time and space scales. We also need to select regions of the ocean where climate induced change is likely to occur. To address the second issue, studies must be designed to measure biological parameters and carbon fluxes that are useful to improve and test model simulations of the ocean carbon cycle.

Many complex oceanic processes (e.g., physical processes that supply nutrients, primary production, particle flux, air-sea CO_2 gas exchange, sinking rates of cold surface waters into the deep sea) respond on time and space scales that span many orders of magnitude from seconds to millennia and from mm to thousands of km. Consequently no field-sampling program can adequately resolve the entire spectrum of variability that exists in the ocean. For this reason we must scale our observations to the spatial and temporal scales necessary to detect and, ideally, predict relevant changes in ecosystems. How can processes that are measured on small spatial and temporal scales appropriately be extrapolated to larger space and time scales? Process and time-series studies often focus on smaller spatial scales (generally with high temporal resolution), while surveys invariably yield results at larger spatial scales (but more often with poor temporal resolution). Time-series studies of various scopes are an important mechanism to scale up results in the time domain and to address variability issues. In a spatial context, global observations from a variety of satellite sensors are excellent means to address spatial and temporal variability of several surface biological and physical processes that control global CO_2 dynamics. Collectively numerical models cover the range of time/space scales but not within a single framework. In particular, improved parameterizations of high frequency time/space variability are required for global ocean carbon models.

Research Philosophy

An integrated ocean C cycle research program should build on past oceanographic research (e.g., WOCE, JGOFS, GLOBEC, IRONEX, CLIVAR, etc.) that has developed a multidisciplinary community of ocean scientists, including those working on field observations, process and laboratory experiments, and numerical models. Many of these programs have developed ideas and information central to the design of ocean carbon cycle research, and leave behind an immense new knowledge base, an unprecedented open data system that encourages cross-discipline analysis, and a new generation of scientists in the evolving field of biogeochemistry.

Also, contributions of individual scientists working independently have been instrumental in developing many of the ideas we build on here.

In the past major advances in our understanding of the ocean occurred following large-scale measurement programs like GEOSECS, JGOFS, and WOCE. Thus it seems likely that medium to large-scale interdisciplinary efforts that operate on large spatial and temporal scales will provide the broad scope necessary for constructing integrated global ocean carbon cycling syntheses. However, any research initiative that will extend over the next decade must recognize the likelihood of unforeseen advances that are not encompassed by our present understanding of ocean biogeochemistry. Such conceptual advances and novel approaches to understanding key portions of the carbon cycle will come from individual investigators or small research groups. Therefore, new initiatives need to maintain the flexibility necessary to accommodate emerging paradigms that simply cannot be predicted at the present time. One method of adding flexibility to a program is to include a range of scales of study from single investigator to large multi-investigator programs. Dedicated support for independent laboratory, field or modeling efforts that have the potential to move carbon cycle research in innovative directions is crucial. These promising new research directions arising from smaller scale projects should be integrated into the larger basin- and global-scale investigations. We should continue encouraging and using both types of approaches within a common planning framework. It is imperative that future ocean C cycle programs, whether based on research by groups or individuals, must be based around a collaborative framework.

An integrated ocean C cycle research program should develop carbon cycle understanding across disciplines and at a variety of organizational levels. First, process studies should be carefully integrated into related efforts that study basin-wide rates, fluxes, and inventories. Local and regional process studies should be extended in space and time, taking full advantage of recently developed remote sensing, ship/platform of opportunity, and autonomous sensing/sampling tools and help further their development. Second, process studies must sample over multi-annual cycles to resolve natural interannual modes of climate variability (e.g., ENSO), and sub-components of the work (i.e., long term time-series stations) should extend further in time. Process studies need to be coordinated with time-series programs. Existing stations need to be extended in duration (although perhaps relying more on autonomous technologies), and new time-series stations initiated. Third, prior to any field studies, a clear vision should be obtained as to how the results would improve modeling and assimilation efforts. In this way focus on relevant aspects of the work is clearly defined. Further, retrospective and numerical modeling studies should be used in developing the sampling strategies and experimental design.

Major Recommendations

We are currently (Summer, 2001) in a period of intense international planning with regard to global carbon cycle research. We intend to provide a scientific framework that identifies and defines major research topics of immediate concern. To that purpose, we provide the following series of recommendations.

Planning, infrastructure and preparation:

Co-ordination: Execute a *coordinated* and *directed* interdisciplinary and interagency program of ocean carbon research in biogeochemistry, ecology and ocean circulation with strong ties to exchanges with the atmosphere and land (see Figure).

Synthesis and modeling: Build on the current JGOFS and WOCE synthesis and modeling programs to develop modeling and assimilation efforts that are executed in conjunction with field programs rather than independent of and subsequent to the field studies. Use the current and planned modeling and synthesis results to design hypothesis driven efforts.

Physical mixing and transport: Develop suitable framework studies of physical transport at scales appropriate to quantify basin or regional biogeochemical sources and sinks. Where possible, identify areas of common interest and resources with studies of physical processes, including basin, meso- and large-scale studies of ocean-atmosphere processes, such as those being conducted by CLIVAR, and global observing efforts, both in-situ (e.g., GOOS) and from space (e.g., NASA initiatives).

Methods development: Continue development of methods for measuring important biogeochemical properties (e.g., pCO_2 and TCO_2, nutrients, iron, optical properties, etc)**.** Continue development of new instrumentation for continuous or autonomous sensing of these properties to expand the time and space domain of observations. Encourage laboratory, *in-situ* perturbation, and field process experiments that focus on acquiring a mechanistic understanding of key biogeochemical and ecological processes governing marine carbon cycle.

Global framework: Develop a framework for studying the global and regional distribution of CO_2 and related tracers in the ocean and initiate strong linkages with the relevant atmospheric and terrestrial carbon cycle communities. These studies provide a link to incorporate results from the proposed process and time-series studies to model anthropogenic and biogeochemical CO_2 fluxes on the basin scale and to determine the magnitude, mechanisms, and interannual variability in these rates.

Basin-wide Studies:

In keeping with a primary goal of the Carbon Cycle Science Plan to understand and constrain estimates of carbon storage in North America, it is recommended that large-scale and long-term series of oceanographic field programs be initiated in the North Atlantic and North Pacific Oceans. An initial emphasis on the North Atlantic and North Pacific Oceans will contribute to broader CCSP efforts to quantify regional magnitudes and variability of northern hemisphere carbon sinks. Although most focus to date has been on the terrestrial sink, there is increasing evidence that northern hemisphere oceans contribute significantly to the total strength and variability of the CO_2 sink. From a carbon cycle perspective, these studies will address the physical and biological mechanisms that cause fundamental differences in the processing of C in these two major northern hemisphere ocean basins. The subtropical regions, because of their large area and convergent water masses, are the dominant site of both biological carbon export and anthropogenic CO_2 inventory. These regional studies will benefit substantially from the

JGOFS time-series stations near Bermuda (BATS) and Hawaii (HOT) that provide more than a decade-long record of key carbon system parameter measurements.

A key measure of the success of the basin studies will be to quantify the magnitude, variability (seasonal to interannual), and biological and physical mechanisms controlling large-scale surface pCO_2 fields and air-sea CO_2 fluxes. The relevant time/space scales are set by the physical circulation (e.g., mesoscale eddies to gyres) and climate variability (e.g., synoptic storms to ENSO/NAO/PDO modes). Extrapolation to the larger scales will require innovative use of remote sensing, in-situ shipboard, autonomous, and ship of opportunity (VOS) measurements, and data assimilation. The basin-scale studies should be integrated with current and emerging atmospheric data sets (e.g. CO_2, O_2/N_2) to better constrain the ocean carbon cycle. This could include instrumenting VOS with pCO_2, temperature, salinity, nutrients, and chlorophyll sensors (in collaboration with CLIVAR), and deploying moorings and drifters in key oceanographic provinces with atmospheric and ocean pCO_2, temperature, salinity, nutrients, chlorophyll, and mixed layer depth sensors.

Southern Ocean Studies:

An important objective of ocean carbon research is to determine the role of the ocean carbon cycle in amplifying or ameliorating natural and anthropogenic variations in atmospheric CO_2, and thus climate change. Although northern hemisphere sources and sinks of carbon are of great current interest and importance, the Southern Ocean is thought to play at least as great a role in governing long term changes in atmospheric CO_2. Furthermore, it is probably the Southern Ocean in which the greatest uncertainties in the carbon cycle, and in the ocean circulation affecting it, lie; the mean state, physical as well as biological, is not presently well understood. Hence it is recommended that studies of the carbon cycle in the southern ocean be undertaken, perhaps later in the decade because of early emphasis on northern hemisphere basins. Time-series measurements in the Southern Ocean, such as those mentioned in the OCTET report using VOS, could be started earlier, however. Theoretical and modeling studies that will help to choose and plan later field studies should also be started as soon as possible. These studies can benefit from recent and current synthesis activities of JGOFS, WOCE and other programs.

Ocean Margins Studies:

Continental margins are the active interface between terrestrial and marine environments. Because the contribution of continental margin processes to global carbon dynamics remains poorly constrained, it is recommended that a series of ocean margin studies be designed to resolve this issue. Current estimates of the global net air-sea CO_2 gas flux are based on open ocean pCO_2 measurements and likely miss most, if not all, of the CO_2 gas exchange occurring in continental margins. Since coastal upwelling and biological production rates are high in these regions and have a substantial impact on surface pCO_2 levels, the role (and temporal response) of the coastal ocean as a net source or sink for CO_2 should be determined. Ocean margins receive substantial terrestrial carbon inputs; have large carbon burial rates and rapid carbon turnover times, yet their role in the ocean's carbon cycle is not well understood. Continental margins, because of the sensitivity of their circulation and biological production to changes in winds, river runoff and anthropogenic inputs of nutrients, are regions likely to be sensitive to climate change.

Specific objectives of new ocean margins studies are better estimates of carbon burial and export to the open ocean, elucidation of factors controlling the efficiency of the solubility and biological pumps in coastal environments, quantification of the influence of margin biogeochemical processes on the chemical composition of open ocean surface waters, and the development of coupled physical-biogeochemical models for different types of continental margins. Biogeochemical processes in margins that are likely to be sensitive to climate change and quantitatively important to basin-scale carbon cycling include terrestrial carbon inputs, calcification, sediment/water column exchanges, and cross-shelf transport / transformation of POC and DOC. Areas of particular concern due to their dominant role in coastal carbon budgets are river-dominated margins and coastal upwelling regions.

***Time Series Studies*:**

The JGOFS time series stations, the Hawaiian Ocean Time (HOT) series and the Bermuda Atlantic Time Series (BATS), have been described as the "crown jewels" of the JGOFS program. Observing the response of ecosystem structure and carbon fluxes to interannual variability in environmental conditions (e.g., climate forcing) provides the most direct and unambiguous strategy to determine the sensitivity of these variables to changing climate. For this reason, continued long-term support of these time series stations is strongly recommended. Because the JGOFS time-series sites represent a narrow range of oceanographic provinces (subtropical) or biomes, it is strongly recommended that new time series, which are representative of higher and lower latitude environments, be initiated. New technological developments in unattended observing systems, including new platforms and new sensors, will be a key issue in augmenting the number of time-series stations in a broad and cost-effective manner. Coordination between the large-scale surveys, the process studies and the time-series stations will be essential to take best advantage of resources, and will benefit from the regional approach suggested here.

Focused Process Studies:

The purpose of focussed process studies is to improve our knowledge of poorly understood ocean processes, regimes and subsystems. These studies should, when possible, be incorporated into basin-wide studies.

Manipulative mesocosm and other whole-ecosystem field studies: Initiate studies to improve our understanding in three ecologically distinct ocean basins (Atlantic, Pacific and Southern) of the role of iron, and other trace metals and factors, and micro/macro nutrients in modulating N vs. P limitation, species succession, community structure modification and climate variation. Temporal variations in iron availability may also be a key factor that controls carbon export from ocean margin systems.

Biological pump studies: Develop studies to improve understanding of the current operation and geographical and temporal (especially interannual) variability of biological pump mechanisms; determine response of the biological pump to global warming, increased stratification, and changes in nutrient limitation regimes. Initiate intensive studies of biogeochemical processes and ecology in the mesopelagic region of net organic matter remineralization (from roughly 100 – 1000 m) in key oceanic provinces, to determine the mechanistic basis of water column remineralization and variations in its efficiency and length scales.

Solubility pump studies: Initiate studies to better quantify and constrain mechanisms regulating air-sea CO_2 exchange and solubility-driven storage of CO_2. Coordinated process studies should also be conducted on ocean physical processes relevant for tracer transport and uptake (e.g., vertical mixing and convection, mixed layer-thermocline exchange, and deep water formation). The air-sea flux of CO_2 is the product of the gas transfer velocity and the air-water gradient in pCO_2. Gas transfer is controlled by physical processes in the air-water boundary region. The models and empirical equations used to describe air-sea CO_2 exchange in global carbon models are uncertain by about a factor of two because of lack of mechanistic knowledge about gas exchange process. Of particular interest is to improve our ability to estimate gas exchange from remotely sensed parameters because this would greatly improve basin and global extrapolations.

Aerosol deposition and transformation: Biogeochemical impacts of trace nutrients from continental sources are not well understood, but processes such as deposition of aerosol iron are believed to influence carbon cycling in many areas of the ocean. Chemical transformations during transport and different deposition mechanisms onto the sea surface (e.g., wet and dry deposition) may greatly alter the nature and amounts of material that reach the sea surface. This can lead to fractionation of aerosols by size and/or composition, in turn affecting bioavailability of chemical species transported by this mechanism. Studies designed to provide the mechanistic understanding necessary to adequately model these transport processes and their influences on ocean biogeochemistry and carbon cycling must be undertaken.

Surface and photochemistry: The sea surface microlayer plays a disproportionate role in near surface turbulent processes controlling air-sea fluxes, cycling of trace compounds of atmospheric origin, and photochemical transformations of dissolved organic material. DOM strongly impacts biogeochemical cycling, especially near the sea surface. Initiate research to develop a predictive understanding of these processes sufficient to extrapolate to the global scale.

Ocean Carbon Inventory Studies:

The inventory, horizontal transport, and temporal evolution of oceanic dissolved inorganic carbon and related biogeochemical tracers (e.g., alkalinity, oxygen, macro and micro-nutrients, dissolved organic matter, carbon isotopes) provide one of the best constraints on numerical models of the ocean carbon cycle, the rate of anthropogenic carbon uptake, and the oceanic responses and feedbacks to natural and anthropogenic climate variability. The 1990's WOCE/JGOFS global CO_2 survey serves as an excellent baseline for tracking and understanding decadal and secular trends in ocean carbon sequestration and internal biogeochemical reorganizations. In conjunction with national and international science partners, a coordinated program should be implemented to routinely characterize the large-scale, global distribution of the ocean carbonate and biogeochemical systems together with the hydrographic and transient tracer data required to interpret and quantify the ocean physical circulation. The horizontal transport and net divergence of these properties should also be measured to link in with air-sea flux and numerical modeling studies. The ocean carbon inventory effort will likely require a combination of zonal and meridional shipboard sections on roughly a 5-10 year time-scale as well as more frequent time-series measurements at key locations to quantify seasonal to interannual variability. Special emphasis should be placed on those regions thought to be particularly sensitive to climate change (e.g., North Atlantic deepwater formation sites, Southern Ocean).

Historical and Paleoclimate Variability Studies*:*
Exploit the abundance of information generated during process studies to improve the interpretations of proxy records preserved in marine sediments; specifically, develop better constraints linking the production, preservation and burial of proxies to the primary variables (parameters related to the physical environment and to the carbon cycle) reconstructed from proxy records

Modeling*:*
Initiate a broad-based program of biogeochemical modeling, including training, as a parallel and fully integrated program element. A diverse set of biological/chemical/physical modeling approaches and scales is envisioned including detailed process models, local and regional site-specific models, diagnostic, inverse and data assimilation models, and global ocean biogeochemical models. Early emphasis should include numerical studies on experimental design and sampling strategies. The program also should develop strong linkages to other climate-system and carbon-cycle modeling efforts. Development of modeling tools that are widely available to the observational community should also be undertaken.

Data Management and Archiving*:*
Maintain and expand data management efforts begun in JGOFS and WOCE to provide both active project data management, timely submission of data through a formal data policy, access to existing and emerging data, and long term archiving. Improve and expand distributed, online access to biogeochemical data sets and synthesis products worldwide.

Standards**:**
Identify, develop and distribute reference materials important to carbon cycle research. Extracting the signal of anthropogenic change from natural oceanic variability requires accurate, long time-series measurements from comparable data sets collected throughout the world ocean. Achieving this will require collection of data with the highest possible standards of reliability and comparability. Accurate analyses of oceanic elements and compounds—dissolved in seawater, in particles in the water column, and in sediments—depend on calibration against a reference standard or series of standards to ensure that measurements are comparable throughout a single analysis, over time, and among laboratories. Comparability among laboratories can only be gained through inter-laboratory calibrations relying on adherence to carefully designed quality assurance plans that include the regular use of reference standards. The development of high-quality reference materials not only provides essential support for measurement programs of large-scale research initiatives, but also ensures that long time-series measurements are accurate and free of measurement errors and drift.

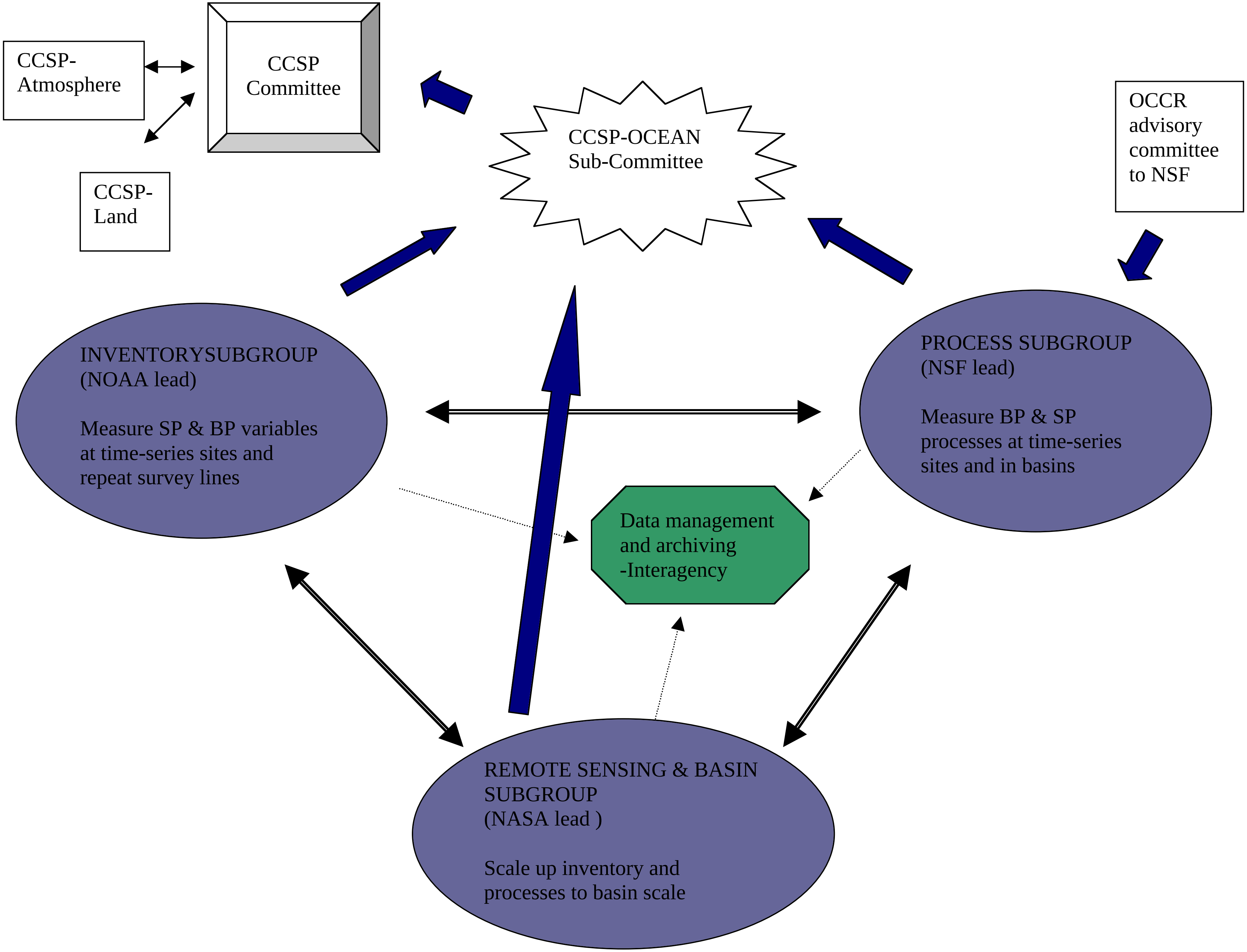
Figure caption

Here we show one possible scenario for how NSF-sponsored research might fit into a larger interagency framework of U.S. research on the ocean carbon cycle. The purpose of this diagram is to show that such coordination is possible. Ocean carbon research is divided for administrative purposes into process, inventory and basin-wide subgroups. All three groups could fall under the aegis of a single committee that could also serve as the “Ocean Sub-Committee” of the CCSP. Major interaction with the CCSP could be at the basin-wide modeling stage, but considerable interaction on process questions is also likely to occur.

The three major ocean carbon cycle funding agencies, NSF, NOAA and NASA, could each take the lead in coordinating one of these subgroups. However, research in all three subgroups could be conducted by all agencies, and considerable “cross-funding” is envisaged. DOE could also be involved through its carbon sequestration program.

All agencies could be involved in coordinating data management and archiving, which could serve as a central and critical clearinghouse for all activities.

Our OCCR committee could continue to provide advice to NSF on their optimum role within such a framework. We envisage NSF’s major role as aiding and abetting the design of process and time-series studies that are carefully coordinated with inventory and large-scale modeling efforts. Individual projects would be primarily small and medium size, but would be coordinated within the larger framework (in time and place). Incorporation into the process component of appropriate modeling, particularly mechanistic models, could be encouraged. NSF’s role in the remote sensing and basin subgroup could include development of techniques for scaling up process study parameters to the basin scale. NSF’s role in the inventory subgroup could include addressing what should be measured and how; new method development for biological and chemical parameters; optimum sampling schemes; modeling.


CCSP-Atmosphere
CCSP Committee
CCSP-Land
CCSP-OCEAN Sub-Committee
OCCR advisory committee to NSF
INVENTORYSUBGROUP (NOAA lead)
Measure SP & BP variables at time-series sites and repeat survey lines
PROCESS SUBGROUP (NSF lead)
Measure BP & SP processes at time-series sites and in basins
Data management and archiving -Interagency
REMOTE SENSING & BASIN SUBGROUP (NASA lead)
Scale up inventory and processes to basin scale