A Global Ocean Carbon Observation System—A Background Report
A Contribution to the Integrated Global Observing Strategy (IGOS)

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Forward

One of the fundamental goals of the Global Ocean Observing System (GOOS) is to improve our understanding and prediction of the climate system by developing a network of sustained ocean observations. Because the carbon cycle plays a crucial role in climate regulation, an ocean carbon monitoring system will be a principal component of the GOOS programme. In collaboration with the Global Climate Observing System (GCOS) and the Global Terrestrial Observing System (GTOS), an integrated strategy for monitoring the global carbon cycle is being developed as part of the Integrated Global Observation Strategy (IGOS), which provides an important framework for integrating in-situ and remote sensing data as well as numerical models.

This document outlines the key scientific questions to be addressed by an ocean carbon observing system, the existing ocean carbon monitoring programmes that constitute an initial observing system, and the new and future network elements required to build a robust, operational program. One large *caveat* must be noted: the background information gathered on the existing operational programmes focuses almost entirely on the open ocean. The inventory required for the continental margins and coastal regions was far beyond the scope of this initial survey, but that exercise is critical to the development of a global system. As mentioned in Section 4, there are a number of international groups who are gathering this type of information, which must be incorporated with the background information presented here before an initial strategy or plan for implementation can begin.

The document draws extensively from a series of ocean carbon cycle meetings, workshops and reports over the last year as detailed below. The document has been and will continue to be circulated widely over the next several months, serving as the basis for a constructive, community-wide discussion on the issues and planning requirements for an ocean carbon observing system. Within the oceanographic community, several national and international programmes such as the U.S. Carbon and Climate Working Group, CLIVAR, LOICZ, and GODAE, and expert groups such as OOPC, IOCCG, and the SCOR-IOC Ocean Carbon Advisory Panel are addressing various aspects of a global ocean carbon monitoring programme. For example, a U.S. NOAA observational planning group for ocean carbon is preparing a document to be released in mid-2001, and an international ocean carbon and tracers group formed during the Ocean Observing System for Climate meeting in St Raphael, France (October 1999) has proposed an observing strategy (Fine et al., 2001). The SCOR-IOC CO_2 Panel has also discussed and proposed certain elements for a monitoring system, outlining ongoing VOS and time-series efforts in each basin. Several major international meetings directly related to the topic were held in September of 2000; namely, the JGOFS EC-US Ocean Carbon Workshop and the SCOR-IOC CO_2 Panel meeting in Paris and an IGBP-SCOR Future of Ocean Biogeochemistry workshop in Plymouth, UK. Further, a broad, vigorous scientific discussion on the state and future of marine biogeochemical research is underway as part of the planning by many ongoing and new national and international science programmes that include JGOFS, SOLAS, LOICZ, OCTET, EDOCC, IGBP Carbon Cycle Framework, the International Ocean Colour Co-ordinating Group (IOCCG), and Operational Coastal Stations. These groups are in basic agreement about the major scientific questions and programme elements required for an ocean observing section as outlined below, and in some cases text has been drawn directly from their reports in creating this document (see Appendix II, References).

Table of Contents

1. Rationale for an Ocean Carbon Observing System

Over the last two centuries, human activities such as fossil fuel emissions, biomass burning, and land use changes have profoundly impacted the global carbon cycle, and present atmospheric CO_2 levels are higher than experienced on the planet for at least the last 400,000 if not the last several million years. Predicting the magnitude of future climate change resulting from greenhouse gas emissions requires the prediction of future atmospheric CO_2 levels for given emissions scenarios. There is an immediate socio-political requirement for better understanding of the global carbon cycle as a consequence of the endorsement of the Kyoto Protocol in 1997. Attempts to limit the future growth of atmospheric CO_2 concentration, however modest, will involve major, and potentially costly, changes in energy and technology policy. The proposed inclusion of certain terrestrial carbon sinks in carbon emission budgeting increases the need to better define global carbon sinks and sources. Further, future assessment of the effectiveness of measures taken to reduce carbon emissions will ultimately be judged by their long-term effect on atmospheric CO_2 levels which in turn requires an understanding of long-term storage changes in all key carbon reservoirs (atmosphere, oceans and the terrestrial biosphere). The ocean is the largest mobile reservoir of carbon on decadal to millennial time-scales, and the long-term sequestration of anthropogenic carbon in the ocean acts to effectively decrease the potential atmospheric radiative and climate impacts. Observational and modeling estimates suggest that the ocean is presently taking up about 30-40% of the fossil fuel CO_2 emissions, but the future behaviour of the oceanic sink is problematic, depending upon possible changes in ocean circulation and marine biogeochemistry.

Public awareness of human impacts on the local, regional and global environment is very high. The interest of the public in having access to accurate information concerning changes to their environment is also very high. One of the major foci of such interest and also concern at the global scale is the effect of human activity and climate on the carbon cycle. Given the major potential economic and technological implications of any attempt to control or redirect global energy policy through global 'carbon management', it is essential that predictions, assessments and models of future behaviour of the carbon cycle are based on sound scientific data and understanding.

Three key scientific questions relevant to the ocean's role in the global carbon cycle arise from current policy-related issues:

1. How large are present-day oceanic carbon sources and sinks, where do they operate, and what processes are controlling them?

2. How will oceanic carbon sources and sinks behave in the future under higher CO_2 and a possibly altered climate and ocean circulation?

3. How and where will we monitor the ocean carbon cycle, assess our forecasts of future oceanic sink behaviour and determine the effectiveness of any deliberate sequestration activities?

A strong emphasis must be placed on quantitative metrics that can be provided to the assessment and political communities as well as the general public. A similar set of questions can be posed for the terrestrial carbon reservoirs. Because of global mass balance, better quantification of the ocean carbon sources and sinks leads to a corresponding reduction in the uncertainties for the terrestrial domain and vice versa. The carbon cycle must be studied as a single, integrated system. The answers to these problems will rely on a combination of carbon-cycle numerical models coupled with and checked against global data sets covering the behaviour of the oceanic, atmospheric and terrestrial carbon reservoirs.

The current ocean carbon observation base, while serving many of the needs of the international science community, is insufficient to these tasks. Only through a coordinated ocean sampling programme and improved, basic scientific understanding of the marine carbon cycle will the overall goal of skilful forecasts of future atmospheric CO_2 trajectories be attained. This document outlines the necessary components of an ocean carbon observing system consisting of three main elements and goals:

i. **in situ observations** on appropriate space and time scales;
ii. relating these data to the surface signal measured by **satellites**; and
iii. improving **models** of the behaviour of the carbon system, including data integration via inverse (diagnostic) modeling and data assimilation.

We also advocate aggressive, linked efforts in ocean process studies, sampling platform and sensor technology development and forward (prognostic) model development and evaluation.

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 behaviour of the terrestrial biosphere by difference will likely be required well into the future. This report acknowledges the global nature of the carbon cycle but addresses only the ocean component and relevant ocean-atmosphere interactions. Companion land and atmosphere carbon cycle observation strategies are being prepared, and the three will be merged to create an integrated observation strategy.

2. Scientific Background

2.1 Introduction

"Ocean waters contain a very large inventory of carbon: ~39,000 gigatons of carbon (Gt C), where 1Gt C is 10^{15} g of carbon. This is 65 times larger than the CO_2 inventory of the atmosphere and approximately 20 times larger than the amount of carbon tied up in terrestrial biota and soils. The ocean's inventory of carbon is estimated to be increasing at a rate of 2 Gt C / yr, thereby absorbing 33% of the "excess CO_2" released annually to the atmosphere. CO_2 that is absorbed by the ocean does not affect the earth's radiation balance, and hence oceanic uptake of excess CO_2 mitigates global warming. In addition, excess CO_2 which is sequestered in the ocean, as opposed to the terrestrial biosphere, is arguably less susceptible to being released back to the atmosphere in the future as a result of mankind's activities. There are many uncertainties in predicting the magnitude of climate change as a consequence of greenhouse gas emissions; a fundamental one is the prediction of future atmospheric CO_2 levels given projected emissions scenarios. Table 1 shows that the global carbon cycle is apparently "unbalanced" to the tune of 1.8 Gt(C)/yr. Both the magnitude and behaviour of this missing sink, although barely significant in the present-day budget given uncertainties in all the "known" terms of the budget, remains critical to the prediction of future CO_2 levels (Wigley, 1993).

Table 1: Global CO_2 budgets (in PgC/yr) based on trends in atmospheric CO_2 and O_2. Positive values are fluxes to the atmosphere; negative values represent uptake from the atmosphere. (From Table 3:1, Prentice, C. et al., 2001: The carbon cycle and atmospheric CO_2, IPCC WG1 Third Assessment Report.)

Source / Sink	1980-1989	1990-1997
Atmospheric Increase	3.3 ± 0.1	2.9 ± 0.1
Emissions (fossil fuel, cement)	5.5 ± 0.3	6.3 ± 0.4
Ocean – Atmosphere Flux	-2.0 ± 0.6	-2.4 ± 0.5
Land – Atmosphere Flux*	-0.2 ± 0.7	-1.0 ± 0.6

*The land-atmosphere flux represents the balance of a positive term due to land-use change and a residual terrestrial sink. The two terms cannot be separated on the basis of atmospheric measurements. Using independent analyses to estimate the land-use change component we obtain for 1980 – 1989 (Houghton 1999, Houghton and Hackler, 1999, Houghton et al., 2000, McGuire et al., subm):

Land-use change	1.6 (0.5 – 2.4)
Residual terrestrial sink	-1.8 (-3.7 to 0.4)

Carbon dioxide which is released to the atmosphere as a result of the burning of fossil fuel partitions between the atmosphere, ocean, and terrestrial biosphere. Monitoring of atmospheric inventories, both directly and through the analysis of air trapped in ice cores, has provided a wealth of data on the historical build-up of CO_2 in the atmospheric reservoir. Modern atmospheric monitoring networks are revealing subtle geographical variability in the temporal increase of CO_2 on a global scale. Of the various sinks for CO_2 listed in Table 1, the atmosphere is clearly the most tractable from a monitoring point of view. Over the timescale of the fossil-fuel CO_2 transient (approximately two to three decades), the atmosphere is well-mixed, and CO_2 resides in a single, readily-measurable form. Hence measurements of a single chemical species made at a limited number of fixed locations on the earth's surface can adequately document the inventory of carbon in this reservoir. Although natural variability, both spatial and temporal, is present in the atmosphere, the long-term increase due to excess CO_2 is readily detectable above this natural 'noise' level.

The next most tractable reservoir for excess carbon monitoring is the ocean. Inorganic carbon is by far the largest pool of carbon found in this reservoir and exists as a limited set of chemical species (dissolved CO_2, bicarbonate, and carbonate ions) whose concentrations can be inferred from measurements. Organic forms of carbon can be measured as bulk properties (eg, dissolved and particulate organic carbon). Mixing and circulation act to homogenize and smooth carbon distributions; however, the mixing time of the ocean is considerably longer that the timescale of the excess CO_2 transient. As a result, the oceanic distribution of excess CO_2 is non-uniform and this introduces a sampling problem for determining changes in its inventory. Natural physical and biological processes create substantial spatial and temporal variability, with amplitudes much larger than the expected excess CO_2 signal, and this also must be taken into account when designing a monitoring strategy.

The terrestrial biosphere reservoir is notoriously heterogeneous, with carbon existing in a multitude of interchangeable forms, and with extreme spatial and temporal variability of biomass present at all scales. In addition, mankind has a direct and rapid impact on terrestrial carbon storage as a result of land-use changes, and plant growth itself may be changing globally as a result of CO_2 fertilization. These factors conspire to create major sampling and measurement problems for time series monitoring.

Most carbon cycle modelers consider that the “missing sink” for CO_2 must lie in the terrestrial biosphere. The reason for this lies primarily with the confidence placed in estimates of oceanic uptake, rather than any particular confidence placed in arguments for alternative, terrestrial carbon sinks. However, resolution of this question of whether the “missing sink” reflects problems with understanding the terrestrial biosphere, or can be accommodated in the oceans, is not the only issue which justifies a long-term ocean carbon monitoring program. While it is by no means certain that the present oceanic uptake estimates based on the present functioning of the oceanic carbon cycle are not themselves subject to systematic bias, the possibility also exists that mankind’s activities will perturb this cycle in the future. “ (excepts taken from *Wallace, D.W.R.1995.Monitoring Global Ocean Carbon Inventories, Ocean Observing System Development Panel, Texas A&M University , College Station, TX. 54 pp.*)

2.2 Current Understanding of Key Processes

The overall scientific motivations of an ocean carbon observation program are to better constrain the mean state, seasonal to decadal variability, and long-term secular trends of the ocean carbon cycle and it's interaction with other reservoirs, in particular the atmosphere and the coastal-land interface. The last decade has seen a tremendous advance in our understanding of large-scale dynamics of the carbon cycle as well an emerging view of key processes. Several general statements can now be made.

2.2.1. Large-scale Sources and Sinks - The fossil fuel carbon source, growth of atmospheric CO_2, and long-term partitioning of the net carbon sink between ocean and land reservoirs are reasonably well known based on the monitoring of atmospheric CO_2, carbon isotopes, and O_2/N_2 ratio levels. The interannual variability in atmospheric CO_2 appears to be largely controlled by terrestrial processes, although with a non-trivial contribution from the ocean, particularly the Equatorial Pacific associated with the El Niño-Southern Oscillation (ENSO). Independent oceanic estimates of anthropogenic carbon uptake from dissolved inorganic carbon (DIC) inventories, net integrated air-sea fluxes, ocean ^{13}C distributions, and numerical physical models produce similar results to the atmospheric constraints at the global level. 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 (e.g., North Atlantic; Southern

Ocean). The 1990's WOCE/JGOFS global survey provides a high quality/precision baseline estimate of the ocean DIC distribution, and preliminary direct estimates of the ocean DIC temporal evolution and horizontal ocean DIC transport are being developed (Wallace 2000, WOCE Book Chapter).

2.2.2. Controls of Anthropogenic CO_2 Uptake by the Ocean - The net ocean uptake of anthropogenic carbon appears to be controlled at present by ocean physics, namely the ventilation and exchange of surface waters with the thermocline and intermediate / deep waters. This uptake, however, is superimposed upon the large background inventory and spatial and temporal gradients of dissolved inorganic carbon (DIC) within the ocean driven by the natural marine carbon cycle. These patterns include substantial net outgassing at the equator and ingassing at high latitudes governed by the physical solubility pump and soft, hard and dissolved organic tissue biological pumps. The seasonal and geographical patterns of export flux of particulate carbon from the upper ocean, phytoplankton standing stock, and marine primary productivity are reasonably well characterized from time series, process studies, and satellite remote sensing (especially ocean colour). The controversy in the mid 1980's over the magnitude and role of dissolved organic carbon (DOC) has led to a resurgence of work in this area and there is a growing understanding of the complexity of factors governing the ocean biological pumps (e.g. iron limitation, nitrogen fixation, calcification, community structure, mesoscale physical-biological interaction).

2.2.3. Temporal Variability of Ocean Carbon - The limited number of long-term ocean time series stations show significant biogeochemical variability from daily 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 interannual variability, and this variability is expressed on regional (several hundred-to-thousands of kilometres) rather than basin-to-global scales. At BATS, a clear correlation has been demonstrated between NAO and ocean hydrography and biogeochemistry variables such as temperature, mixed layer depth, primary production, and total CO_2, suggesting that the North Atlantic is likely responding in a coordinated, basin-wide manner to interannual variability (Bates, N.R., 2001a. *Interannual changes of oceanic CO_2 in the Western North Atlantic Subtropical Gyre*. Deep-Sea Research II, *in press*). 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 interannual variability in export production and seasonal oxygen fluxes.

The slower, decadal time-scale ocean responses (e.g. changes in nutrient stocks and community structure) are not as well characterized as the interannual response, though there is tantalizing evidence for large-scale biogeochemical regime shifts (or perhaps secular trends) (Karl, 1999; Ecosystems). Distinguishing signal from noise in this environment is often singularly difficult. The problem is further compounded by potential human-induced perturbations to the natural ocean carbon cycle.

2.2.4. Possible Responses to a Changed Climate - 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., Nature, 1998). A complete understanding of the modern ocean circulation and potential changes in response to greenhouse warming is not presently available, and significant differences exist between coupled ocean-atmosphere simulations. A much better quantitative description of ocean circulation and the processes governing climate response are required. The climate impacts on the natural biogeochemical system and possible feedbacks on atmospheric uptake are even more problematic and depend upon a number of mechanisms (Doney and Sarmiento, 1999; U.S. JGOFS Synthesis and Modeling Project report). Potential effects include:

i. decreased calcification from lower pH and CO_3-ion concentrations resulting from anthropogenic CO_2 uptake (Kleypas et al., Science 1998; Reisebell et al, 2000 Nature);
ii. decreased nutrient supply (vertical) and in some regions enhanced, effective-surface-layer light supply leading to often opposing regional changes in primary productivity;
iii. possible alteration in large-scale nutrient stocks and community composition;
iv. modifications in iron fertilization affecting the high nitrate-low chlorophyll (HNLC) regions such as the Southern Ocean and possibly subtropical nitrogen fixation.

Most, if not all, of the previous global assessments of the oceanic carbon cycle have not fully accounted for the carbon fluxes and dynamics on continental margins and in the coastal ocean. The waters of the coastal area interact strongly and in complex ways with the land, atmosphere, continental shelves and slopes, and the open ocean. The specific rates of productivity, biogeochemical cycling, and organic/inorganic matter sequestration are higher in coastal margins than those in the open ocean, with about half of the global integrated new production occurring over the continental shelves and slopes. The high organic matter deposition to the sediments and interactions at the sediment-water interface raises the importance of sedimentary chemical redox reactions (e.g. denitrification, trace metal reduction and mobilization), with implications for the global carbon, nitrogen, phosphorus and iron cycles. The fate of the 0.6 Pg/y of carbon deposited to estuaries and the coastal ocean by rivers is not well quantified, nor are the net coastal air-sea CO_2 fluxes and the material exchanges between the coastal region and the open ocean. Finally, the direct and indirect human perturbations to the coastal environment (e.g. pollution, nutrient eutrophication, fisheries) are large, with important impacts on marine ecosystems (coral reefs, spawning grounds) and society (commercial fisheries, tourism, human health and aesthetics). Nearly 60% of the world's current human population lives within 100 kilometres of the coast, and this number is increasing every year as people move from continental interiors to urbanized centres on the coast or to immediately adjacent riverine watersheds.

2.2.5. Future Directions for Research - A number of measures have been identified and listed below that are required to move toward the overall scientific goal of better constraining the ocean carbon cycle. A comprehensive ocean carbon observing system and a long-term science research strategy are essential for undertaking them.

1. Quantify the basin-scale and seasonal to interannual air-sea fluxes, phytoplankton biomass, and productivity in the context of natural modes of climate variability.
2. Monitor the temporal evolution, regional patterns and horizontal transports of ocean DIC, biogeochemical species (e.g. nutrients, dissolved iron, oxygen, DOC), transient tracers, and ocean ventilation.

3. Characterize the time-space variability of marine biogeochemistry and extrapolate from local process level information to basin and global scales.
4. Assess the role of the coastal-ocean margins in the global carbon cycle and the impacts of direct and indirect human perturbations.
5. Accelerate development of quasi- and fully autonomous ocean sampling platforms and biological/chemical sensors.
6. Improve mechanistic understanding of biological, chemical, and physical processes that control present and future oceanic (and ultimately atmospheric) carbon storage including mechanisms that are only weakly active at present.
7. Provide framework for assessment of results through diagnostic modeling, data assimilation and comparison with atmospheric and terrestrial constraints.
8. Use observations to initialise, evaluate, and develop parameterizations for prognostic global ocean biogeochemical models.

3. General Structure of an Observing System

Historically, a majority of in-situ ocean biogeochemical observations have been carried out by individual scientists working on specific research problems. JGOFS was the first large scale international program executed to systematically evaluate biogeochemical processes over a variety of oceanic provinces. This approach has accelerated our understanding of these processes far beyond what could be achieved by piecing together information from independent, disjoint investigations. A major challenge for the future is to coordinate the diverse suite of in-situ, remote sensing, and numerical studies in terms of field sampling and data synthesis.

Individual methods for sampling the ocean have their unique strengths and weaknesses that must be addressed in designing an observing system. Most oceanographic process studies are necessarily limited to the time and space scales of one or more research cruises or expeditions. Satellite remote sensing provides critical information on high-frequency variability, large-scale spatial patterns, and seasonal-to-interannual signals. However, only a few parameters can be measured from satellites and for many properties, ocean colour, for example, only for the surface layer. Hydrographic surveys, such as those conducted by WOCE and JGOFS, offer a snapshot of the basin-to-global scale distributions, but not their temporal evolution. Long, in-situ time series are invaluable, but to track long-term, secular trends, they should be of decadal to multi-decadal span to extend over several cycles of the natural climate variability modes. Collectively, numerical models cover the range of time/space scales, but not as yet within a single framework.

Traditional shipboard oceanographic surveys will remain a necessary element of any 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 to address 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. The rapid evolution and eventual outcome of these technological developments, however, are difficult to foresee. The detailed planning and optimisation 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.

These new tools could be used to fill a significant gap between the local/regional spatial scales measured by time-series and process studies, and the basin-to-global scales derived from hydrographic surveys. Gyre-to-basin scale regional observing systems are required that are more extensive in time and space, but less intensive (at particular points) than more traditional process studies. Such programmes would allow for much better quantification of the magnitude and interannual variability of basin-scale air-sea CO_2 flux, a quantity required by atmospheric inversion models to constrain terrestrial processes, as well as the underlying physical and biological driving factors. Regional carbon observing systems should be designed to capture the time and space scales of the dominant climate variability modes and can leverage complementary climate observing programs. By necessity, they will need to incorporate autonomous sensors/platforms and Volunteer Observing Ship (VOS) data, as well as observations from oceanographic research ships, relying on satellite remote sensing and data assimilation for time-space extrapolation over the full domain.

A variety of key mechanisms governing how the ocean carbon system may respond to climate change are poorly understood, and detailed process studies are required. These process studies will be carried out by individual scientists, as well as national, regional, and international groups over time scales of about 1-5 years. The results from these programmes will be crucial for the further planning and development of the full monitoring system.

Finally, numerical modeling and data assimilation in particular will play a crucial role in the synthesis and interpretation of observational data. Increasingly, inverse modeling techniques utilizing constraints imposed by atmospheric, oceanic and terrestrial measurements are being developed and applied. Both forward and inverse modeling approaches rely on access to a set of relevant and high-quality observations covering regional and global scales. Modeling considerations should be considered in the sampling network design from the beginning.

Given these constraints and the science and monitoring objectives described above, the basic structure of an ocean carbon observation system is generally well agreed upon, though with implementation differences arising in various plans and strategies (e.g. see Sarmiento and Wofsy, 1999; Fine et al, 2000). Key elements include:

Basin-Scale Surface Observations (4.1)

- automated pCO_2 sensors on Ship Of Opportunity (SOOP) and VOS lines
- upper ocean biogeochemical and ecological surveys
- instrumented surface drifters, floats, and moorings

Large-Scale Inventories (4.2)

- repeat specific WOCE hydrographic lines on 5-10 year cycle
- carbon system, biogeochemical variables, and transient tracers
- horizontal transport estimates

Time Series Stations (4.3)

- ecosystem dynamics augmented with carbon system and tracer data

- coordinated network over wider range of biogeographical regimes
- continuity over decadal to multi-decadal time spans

Satellite Remote Sensing (4.4)

- ocean colour (biomass, primary productivity, community structure, physiology, coloured dissolved organic matter)
- air-sea gas transfer (wave characteristics, wind speed and friction velocity, sea surface temperature, atmospheric pressure)
- remote sensing requirements for ocean carbon cycle science

Coastal Observations (4.5)

- riverine and groundwater inputs
- biogeochemical cycling
- time series
- sediment-water interactions
- coastal-open ocean exchange

Atmospheric Monitoring (4.6)

- CO_2, carbon isotopes, and O_2/N_2 ratios
- atmospheric inversion models
- dust (trace metals) and nutrient deposition
- meteorological forcing

Numerical Modeling (4.7)

- diagnostic and inverse models
- pilot ocean carbon data assimilation system
- prognostic model hindcasting and model-data evaluation.

In addition, three essential components for future system planning are:

Technology Development (Section 5)

- autonomous sensors for biological and carbon system parameters
- moored buoys
- drifters
- profiling floats, gliders, and autonomous underwater vehicles

Process Studies (Section 6)

- physical processes in relation to the carbon cycle
- the solubility pump
- the biological pump

In Sections 4.1-4.3, a summary table provides an overview of on-going and planned programmes that form the base elements for an initial observing system. At the moment, however, these programmes are often disjoint and/or too sparse to provide a complete picture of the ocean carbon cycle. Progress in the organisation and overall coordination of the system development can be made by:

1. identifying and supporting programme elements that are currently in operation (e.g., time series stations and SOOP / VOS lines) or that are in the planning stages;
2. convening and encouraging international meetings of expert groups to refine observing system requirements needed to reach scientific and operational monitoring goals;

3. maintaining the existing DIC / Alkalinity Certified Reference Materials (CRMs) programme, expanding into other standards (e.g. nutrients) and intercalibration activities (e.g. iron);
4. analysing and synthesizing recent and historical ocean carbon cycle data sets (while not a sustained operational activity, these results are paramount for the design and application of the observing system);
5. developing an iterative approach to the strategy and planning for ocean carbon observations based on process study results and technological advancements;
6. enhancing data management and distribution capabilities as well as making strong commitments to public data sharing;
7. promoting a cooperative synergy with other physical, chemical and biological ocean field efforts with special emphasis on WCRP (CLIVAR), IGBP Programmes (JGOFS, LOICZ, GLOBEC) and GOOS.

4. Observing System Elements

This section defines the observing system in terms of:

- specific scientific objectives;
- sampling requirements to achieve these objectives;
- sampling and observing methods available;
- existing observation programmes;
- enhancements needed / gap identification;
- research and development required

Summary tables of sampling requirements and existing system elements are given in Section 7 of this document. The initial strategy and plan for the implementation of the ocean carbon observing system can only be developed through an iterative process, collecting information on existing monitoring programmes and establishing consensus among the international scientific community on research and monitoring goals. Once this is done, gaps in the existing system, both spatial and temporal (continuity), must be identified and an international / intergovernmental mechanism established to secure support and commitment for implementation of a global observation network. *This document has been developed to serve as a first step towards developing such an initial plan and strategy for ocean carbon observations*. There is already strong international support for this programme, and the results of this planning effort will be integrated with similar plans from the terrestrial and atmospheric carbon observation communities to establish a global carbon observation strategy.

4.1 Basin-scale Surface Observations

Application - One of the basic products of an ocean carbon observing system will be routine, quantitative estimates of the basin-scale ocean-atmosphere exchange over seasonal to interannual time periods. Net air-sea flux estimates are typically derived by combining air-sea pCO_2 differences, derived from underway surface pCO_2 systems, with gas transfer velocity estimates. Gas transfer velocities are often approximated as a function of wind speed, taken from either climatologies or numerical weather centre analysis products. More recently, transfer velocity is being related to satellite derived measurements of surface winds (scatterometer) and surface roughness (scatterometer and altimeter). Spatially and temporally extensive in-situ sampling of surface pCO_2 levels is needed as well as sampling of other ecosystem and biogeochemical data to place the pCO_2 data in proper context.

Sampling Requirements - "How many such observations of pCO_2 are needed ? We can calculate an order of magnitude for the number of observations needed to define the global aid-sea flux to a given accuracy. For example, in the North Atlantic (probably the ocean basin in which pCO_2 is most variable and best studied), it has been found that during the spring bloom the 1-s uncertainty at a given point due to natural variations is ±10 µatm. This suggests that ~100 independent observations would be required to define the mean value at a given point and season to within ±1 µatm. Globally, an error of 1 µatm in the mean would lead to an error in the flux into the ocean of order 0.2 Gt C/yr (Tans et al., 1990). In the ocean, the autocorrelation time and length scales are those appropriate to the passage of eddies (i.e., one month and 100 km). An adequate coverage might therefore require 100 observations for each 100 x 100 km box of ocean for each month of the year.

Such coverage for every part of the global ocean is well beyond our reach. However, the position is not in reality so bleak. Internationally, a considerable effort is now underway to document pCO_2 in the surface ocean, and its dependence on season, position, and interannual changes. There are now no major ocean regions in which there are not at least some measurements, and many areas are increasingly well covered. Most of the global oceans appear to be more homogenous in terms of surface pCO_2 that the North Atlantic. Furthermore, while such dense coverage cannot be obtained for every part of the ocean, it may be obtained along the routes that merchant ships frequent and in other regions from equipped drifters." (quoted directly from *The Ocean Observing System Development Panel. 1995. Scientific Design for the Common Module of the Global Ocean Observing System ad the Global Climate Observing System: An Ocean Observing System for Climate. Department of Oceanography, Texas A&M University, College Station, Texas, 265*.)

Methods

1. Ships - Shipboard underway pCO_2 measurements from oceanographic research vessels, VOS, and SOOP vessels employs a relatively mature technology for measuring surface pCO_2. For example, a large global surface pCO_2 data set was collected on the WOCE-JGOFS global hydrographic programme supplemented by previous research surveys (TTO, SAVE). T. Takahashi (Lamont-Doherty) has developed an extensive, historical VOS data set for the North Atlantic and Pacific. Coverage of the pCO_2 field in the Equatorial Pacific, a region of known large variability in air-sea CO_2 exchange because of ENSO, has been monitored for the last several years from an underway system on the TAO array servicing ship.

While much experience has been gained over recent years, pCO2 measurements from VOS can still be problematic because there are no certified reference materials. In a recent seagoing intercomparison study (Körtzinger et al., 1999), seven fCO2 systems of different designs from different research laboratories were compared while underway in the North Atlantic Ocean. When the fCO2 results were corrected to a common temperature, three systems agreed to ±2 µatm. The remaining four systems showed offsets of up to 10 µatm. The consequences of this uncertainty are clear when we consider that an error of 1-2 µatm in the global air-sea disequilibrium translates to uncertainty in annual mean ocean uptake of about 10% (0.2 PgC /

yr). A set of best practices by the leading researchers in this area is urgently needed. For the initial observing system, however, it is important to recognize that even with potential biases, VOS is still very useful for characterizing seasonal to interannual variability on regional scales, where tight constraints on global net flux are not required.

Continuous underway systems have been developed for other properties including nutrients and chlorophyll as well, but to date these systems have been mostly deployed on research vessels. Discrete water samples also can be collected underway for shipboard or later shore-based analyses. The operational resupply transects offer an excellent opportunity for routine, basin-scale ecosystem observations. For example, nine Atlantic Meridional Transect (AMT) cruises between the UK and the Falklands participated in the SeaWiFS project. There were sampling limitations because of ship schedule and coordination issues. Nevertheless, the few measurement suites (e.g., optics, pigments, CTD casts) collected on all cruises provide a valuable data resource.

One limitation of underway pCO_2 measurements is that they require a technician onboard to operate and monitor the system. Recently, NIES / JAMSTEC have developed a system that can be operated by a trained member of the ship's crew rather than a dedicated technician, which has substantially reduced operational costs. In order to augment the use of this technique, these underway systems must be made more autonomous than at present.

2. Buoys - Prototype pCO_2, bio-optical and nutrient sensors as well as discrete water samplers (e.g. trace metals) have been tested for either surface drifters and/or moorings. Initial work on biogeochemical sensors (particulate inorganic and organic carbon) for profiling *Argo* floats has also begun. Although considerable progress has been made in the development and use of autonomous surface drifters measuring pCO_2, these devices are still in the research phase and ground-truthing of sensors over the long-term is critical. In addition, the present costs involved make prohibitive wide scale deployment on drifters that are not recoverable. Further development and large scale production may reduce these costs, but it may also be the case that a monitoring system using these biological and chemical sensors must be designed in such a way that the drifting packages are recovered and later redeployed. Combining moored, autonomous chemical and biological sensors with existing and new time series efforts and large-scale surveys will allow the new measurements to be validated in the field and related back to the physical and biological forcing. This is essential for basin to global scale extrapolation. Further work is needed to determine if large-scale surface pCO_2 can be quantitatively estimated from satellite-based algorithms. In general, the development of these autonomous instruments and platforms are currently in the research phase, but could be transferred to operational mode in the near-term (5 year) horizon.

The Existing System **–** The VOS and SOOP lines currently making pCO_2 measurements are listed in the table below. Also listed are lines that have been planned to be implemented over the next 2-3 years. The North Pacific has the best coverage owing to the pioneering work of the NIES / JAMSTEC *Skaugran, Alligator Hope* and *Alligator Liberty* vessels, as well as the TAO servicing ship in the Equatorial Pacific. In the North Atlantic, the Antarctic resupply vessels and the Continuous Plankton Recorder provide limited coverage. Several lines, however, are being planned for various North Atlantic transects. The European project, Carbon Variability Studies by Ships of Opportunity (CAVASOO), has recently been funded for a 3 year period.

No operational drifters currently make pCO_2 measurements, although a number of short-term research programmes are ongoing. The use of moored instruments for surface pCO_2 measurement is discussed in the Time Series Section 4.3.

VOS and SOOP Lines

Operational	**Basin**
TAO servicing ship	Equatorial Pacific
OISO servicing ship (Kerguelen Island – Crozet – Amsterdam Islands)	Southern Ocean
Alligator Hope (Tokyo – Vancouver)	North Pacific Transect
Alligator Liberty (Yokohama – Panama)	North Pacific – Central Pacific Transect
Ryofu-Maru and Keifu-Maru (JMA) – 137E, 165E	North Pacific
Atlantic Meridional Transects (UK – Antarctica)	Atlantic Meridional transect
Hesperides	North Atlantic
Line 'P' (Labrador Sea)	North Atlantic
Polarstern	North Atlantic – Pole to Pole
CAVASOO Programme (EU) 3 years	North Atlantic
Continuous Plankton Recorder	North Atlantic

Planned	**Basin**
Denmark – West Greenland	North Atlantic
Hamburg – Halifax	North Atlantic transect
UK – Jamaica or Miami	North Atlantic transect
GeP&Co (Le Havre – Nouméa)	North Atlantic, Caribbean, South Pacific
Hong Kong-Mexico (Manzanillo)	North Pacific transect
Peru (Callao)-Japan (Yokohama), west bound, by NIES/JAMSTEC	North Pacific transect

Enhancements to the Existing System – While the North Pacific and North Atlantic have some coverage, routine measurements in the Indian Ocean, South Atlantic, and South Pacific are sparse. The table below lists lines that have been discussed at various international ocean carbon meetings based on identified ship routes. Of particular interest is the possibility of a NIES / JAMSTEC-sponsored VOS operating between South Africa and Japan via the Indonesian Seas. In the South Atlantic, a dedicated servicing ship for the PIRATA array as is used for the TAO array would be an invaluable addition to the carbon monitoring network. The various tracks of Antarctic resupply vessels must be investigated further to determine the possible coverage for the South Pacific and South Atlantic, as well as Southern Ocean sectors.

Possible Additions	**Basin**
Miami – Spain / Straits of Gibraltar	North Atlantic transect
Norfolk, Virginia – Bermuda	North Atlantic
Southern Ocean, Tasmania to Dumont D'Urville, Antarctica	Southern Ocean
Canada (Vancouver)-Australia (Brisbane), IOS, Canada	Pacific Meridional transect
New York – Halifax and Reykjavik	North Atlantic
PIRATA servicing ships	South Atlantic
Polarstern AMT line	Atlantic Meridional transect

US Coastguard Icebreakers - Seattle to Antarctica	Pacific Meridional transect
South Africa – Japan via Indonesian Seas (Japan VOS)	Indian Ocean

Research and Development -
With respect to basin-scale surface observations, the Initial Observing System should:

1. Expand operational VOS network for pCO_2;
2. Develop and augment unmanned or crew-operated underway pCO_2 systems;
3. Establish routine collection of carbon system, biogeochemical, bio-optical and ecological parameters on VOS network;
4. Develop and deploy instrumented floats/drifters for DIC, pCO_2 and bio-optics.

4.2 Large-scale Inventories

Application **–** Observations of large-scale oceanic distributions of carbonate system variables and other relevant biogeochemical species provide important information on the patterns and rates of organic matter export, subsurface remineralisation, air-sea exchange, and anthropogenic carbon storage. They also serve as key constraints on ocean biogeochemical numerical models. Transient tracer fields offer insight on physical mixing, circulation pathways and transport rates that have a direct impact on the ocean's ability to absorb excess atmospheric CO_2. Preliminary data analysis efforts have shown success at estimating basin-scale meridional transport of biogeochemical species including DIC. The combination of inventory measurements, air-sea flux estimates, and transport calculations allows for closure of the carbon mass balance and, similar to heat transport, provides a valuable measure for testing the skill of diagnostic and prognostic models. Combined with atmospheric measurements, a well-planned series of repeat sections can be used to close the global carbon budget on decadal scales. The results would provide a strong constraint for current atmospheric inversions used to partition carbon among the atmosphere-ocean-land system, and the estimates of transports through the sections may provide additional valuable information to identify terrestrial uptake of anthropogenic CO_2 on regional scales.

The mapping of ocean hydrographic properties, including oxygen and nutrients, dates back to the 19th century, and a number of important global and regional carbon system and transient tracer surveys have been conducted over the last several decades. These include the seminal GEOSECS programme in the 1970s, the North and South Atlantic surveys in the 1980s (Transient Tracers in the Ocean (TTO) and South Atlantic Ventilation Experiment (SAVE)), and the recent, comprehensive WOCE-JGOFS Hydrographic Survey (with high precision carbonate system measurements) in the 1990s. Repeat occupations of the WOCE hydrographic lines, needed to constrain natural variability and secular climate change of the ocean carbon cycle, are being pursued by a number of countries (Southern Ocean and Eastern Indian Ocean, Australia; Labrador Sea, Canada; Western Pacific, Japan). However, these efforts do not have sufficient global coverage nor are they organized in any long-term international framework. Because of their expense and logistics, large-scale surveys are conducted only infrequently in time, giving us a picture of the "mean state" of the ocean that may not be representative of the actual long-term average distributions because of seasonal, interannual and decadal timescale variations. It is now known, for example, that the WOCE years were very unusual from many standpoints and represent ocean climate extremes rather than norms. This can be remedied to a degree by using long-term time series stations and a limited set of higher frequency repeat sections (seasonal to annual) to characterize the variability and to bridge between re-occupations.

Sampling Requirements / Methods - Shipboard surveys for each basin are needed on a 5-10 year time-scale to track the penetration of anthropogenic CO_2, to search for changes in ocean circulation, and to monitor the natural biogeochemical cycling and potential response to global climate change. The surveys should include standard hydrography (WOCE/JGOFS parameters, T, S, nutrient, oxygen) plus the carbonate system (DIC, alkalinity, pCO_2, pH), transient tracers (radiocarbon, tritium, and the halocarbon/CFCs), and additional biogeochemical species (iron, dissolved organic carbon and nutrients, particulate organic and inorganic carbon). The WOCE-JGOFS survey did not include a number of key parameters; iron, for example. Our limited knowledge of the vertical distribution of dissolved iron and how iron is actually cycled in the ocean is currently a major hurdle for replicating the observed distributions of phytoplankton and macronutrients in numerical models. At present, full-depth profiles of DIC and alkalinity at required accuracies are attainable only through shipboard sampling and the use of certified reference materials (CRMs). The long-term continuity of the ocean DIC CRM program is therefore critical. Developmental work on autonomous carbonate system sensors that could be deployed on profiling floats is promising, at least for quantifying the seasonal cycle and interannual variability in the thermocline.

The Existing System - The operational and planned hydrographic sections are given below. Because the sections are only carried out on multi-year time-scales, longer-term planning (continuity) is difficult to determine.

Hydrographic Sections

Operational	**Basin**
Eastern Indian Ocean I10, I5E, 95ºE from 9ºS to 32ºS	Indian
48ºN Transect , BSH and IfM-Kiel (WOCE line A2)	North Atlantic
Labrador Sea by BIO (WOCE line AR7W)	North Atlantic

Planned	**Basin**
SR3 Southern Ocean, Hobart to Antarctica along 140ºE	Southern Ocean (Pacific Sector)
P15S from 50ºS to Equator	South Pacific
JAMSTEC plans to occupy one Pacific hydrographic section every two years; first target is P17 and next is P3. Survey includes full CO_2 and tracer measurements	Pacific Meridional transect (P17) and North Pacific (P3)

Enhancements to the System **–** Based on the scientific requirements outlined above, a series of 5-10 year transects has been suggested for key locations:

Possible Additions	**Basin**
A2N line – BSH	North Atlantic
24 N Atlantic Line	North Atlantic
Transect, Greenland Sea at 75N	North Atlantic
Transects, Fram and Bering Straits	North Atlantic
North Atlantic Boundary Current sections (55ºW, 26.5ºN, 35ºW)	North Atlantic
High Latitude Southern Ocean / I9S Southern Ocean	Southern Ocean (Indian Sector)
At least 1 zonal and 1 meridional section per basin	All Basins; minimum requirements

Research and Development -
With respect to large-scale inventories, the Initial Observing System should:

1. Implement reoccupation of select WOCE-JGOFS lines on a 5-10 year cycle for hydrography, the carbonate system, transient tracers, biogeochemical species and horizontal transport
2. Add carbonate species and transient tracers to existing and new time-series stations as well as a smaller set of seasonal-to-annual repeat sections;
3. Monitor large-scale ocean physical circulation especially near and downstream of high latitude intermediate and deep water formation sites;
4. Develop alternative approaches/technologies to full-depth hydrographic surveys but keeping the same accuracy for carbonate system variables (DIC = 1-2 µmol/kg; Alkalinity = 2-3 µmol/kg);
5. Maintain carbon CRMs and develop CRMs for other species (e.g. nutrients);

4.3 Time Series

Application - Long term time series measurements are crucial for characterizing the natural variability and secular trends in the ocean carbon cycle and for determining the physical and biological mechanisms controlling the system. The annual anthropogenic CO_2 uptake by the ocean is small relative to the seasonal magnitude of the natural carbon cycle as measured by either the surface net primary production or net community production, the latter balanced over annual time and long space scales by the downward and sideways flux of advected dissolved organic matter and sinking particles. The surface carbon export flux is a dominant factor governing the vertical distribution of ocean DIC and the pre-industrial atmospheric pCO_2 level. Year-to-year variations in physics (e.g. upwelling and downwelling), 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 the prognostic models used in future climate projections. Time-series stations (particularly when accompanied by moorings) are also invaluable for developing and testing autonomous sensors and as focal points for process studies.

Sampling Requirements - "Variability on the vertical scale imposes further constraints on observations of biogeochemical processes. Vertical length scales for photosynthesis in the open ocean are on the order of 10-30 m. Critical photosynthetic processes occur at depths that cannot be monitored by satellites, VOS or drifters. Vertical length scales for the remineralisation of carbon to CO_2 are longer, on the order of 100-200 m for the top kilometre of the ocean. All indications to date point to large horizontal length scales (1000s of km), although mesoscale eddies and rings introduce additional variability in vertical structure. At the very least, monitoring at time series stations requires measurements at the appropriate vertical scales for different representative ocean regions.

In terms of detecting the long-term change in CO_2 storage in the deep ocean arising from increasing anthropogenic levels of atmospheric CO_2, accuracy becomes a prime concern, because variability in deep oceanic waters is not nearly as strong as in the upper ocean. To be able to detect the signal after 10 years, the required accuracies are at minimum ±1 µmol / kg for total CO_2 and ±1 µmol /kg for total alkalinity. To be applied on a global scale, the calculation of storage from the measurements must resolve the effect of the mixing of different water masses. There is hope that this difficulty can be circumvented by the use of transient tracers such as ^{3}H-He, ^{14}C, and CFCs." (quoted directly from *The Ocean Observing System Development Panel. 1995. Scientific Design for the Common Module of the Global Ocean Observing System ad the Global Climate Observing System: An Ocean Observing System for Climate. Department of Oceanography, Texas A&M University, College Station, Texas, 265*.) Based on the rate of change and current uncertainty of total CO_2 in the surface ocean measured over a 10 year period at BATS, a time series of at least 5-8 years is required to statistically determine a secular increase in total CO_2. The situation is similar for pCO_2, where a time series of approximately 10 years is required to statistically determine any increase in seawater pCO_2 due to the anthropogenic transient (Bates, N.R., 2001a. *Interannual changes of oceanic CO_2 in the Western North Atlantic Subtropical Gyre*. Deep-Sea Research II, *in press*).

Methods - The best known open-ocean time-series currently operating are the more than decade-old U.S. JGOFS stations near Hawaii (HOT) <http://hahana.soest.hawaii.edu/hot/hot.html> and Bermuda (BATS) <http://www.bbsr.edu/cintoo/bats/bats.html>. The HOT and BATS monthly data include both carbonate-system variables and more traditional biogeochemical data (e.g. primary productivity, chlorophyll, nutrients, near-surface sediment traps) and have led to a number of key discoveries (e.g. demonstration of an anthropogenic uptake signal in surface DIC; importance of nitrogen fixation in subtropical Pacific). Products from these programmes include high-quality data sets and on-line tools from programme web-sites for searching and subsetting the available data.

The Existing System - Time series of plankton species and abundance are routinely made through the Continuous Plankton Recorder Programme of the Sir Alister Hardy Foundation for Ocean Science (UK) for selected regions of the North Atlantic. Fisheries and other biologically based agencies also provide time series data for a few locations, open-ocean as well as coastal. In addition there is a wide variety of coastal biogeochemical and ecological time-series programmes, though not all include a direct focus on the inorganic carbon system (e.g. LTER sites, LEO-15, CALCOFI, MBARI Monterey Bay).

Several groups have deployed fully autonomous pCO_2 sensors on moorings or drifters, including, for example, the Bermuda test bed mooring, Ocean Station P, the DYFAMED site in the Mediterranean, the Equatorial Pacific, the Greenland Sea, and Monterey Bay. The Marine Optical Buoy (MOBY) off Lanai, Hawaii is the primary calibration site for SeaWiFS, MODIS and other future ocean colour missions. The continuation of this facility is critical, at least until alternative platforms and methods can be verified. The SIMBIOS project has supported moored optics in the equatorial Pacific and on the Bermuda Test-bed Mooring, but data quality has been an issue due to bio-fouling and other instrument calibration issues. More recently, better methods and technologies for these deployments have improved data quality, but evaluation is ongoing. Ultimately, what is required is a global network of quasi-autonomous ecological, bio-optical, and biogeochemical observations; such a network would serve multiple purposes including as the basis for calibrating, validating, and adding value to remotely sensed ocean colour data.

A number of shorter-term, sometimes lower temporal resolution, open ocean time-series stations were carried out (some still ongoing) in the 1990s under international JGOFS. Details are given in the table below.

In February 2001, the Atlantic Network of Interdisciplinary Moorings and Time Series for Europe (ANIMATE) programme was funded by the European Community. This programme will establish three new mooring-based, carbon-observing time-series sites in the North East Atlantic. These moorings will be equipped with near-surface pCO2 sensors, seacats, as well as time-series sediment traps. This programme is strongly linked to the new EC-funded set of VOS lines in the North Atlantic.

There are a number of preliminary planning efforts that are focusing on sparsely sampled areas. Planning is continuing between Australia and France concerning coordination of Southern Ocean Observations. In addition, there may exist in the future the possibilities of some significant programmes between Germany, Indian, and Japan in the Indian Ocean using VOS and moorings, where long-term sediment trap moorings are already in place.

Time Series Stations (ship and mooring based)

Operational	**Basin**
HOT (Hawaii) *ship-based and mooring-based*	North Pacific
BATS (Bermuda) *ship-based and mooring-based*	North Atlantic
Ocean Station 'P' (North Pacific) *ship-based*	North Pacific
ESTOC (Eastern Subtropical North Atlantic) *ship based and mooring-based*	North Atlantic
KNOT (44°N, 155°E), operational from 1998-2000	North Pacific
TAO Array (Carbon sensors operated by MBARI and PMEL) *mooring-based*	Equatorial Pacific

Funded (February 2001)	**Basin**
Northeast Atlantic, Porcupine Abyssal Plain – *mooring deployment*, IfM Kiel and partners in the UK (ANIMATE)	North Atlantic
ESTOC - *mooring deployment,* IfM Kiel and partners in Spain (ANIMATE)	North Atlantic
Irminger Sea - *mooring deployment*, IfM Kiel and partners in Iceland (ANIMATE)	North Atlantic

Enhancements to the System – While a number of time series stations currently operate globally, most do not make measurements of carbonate system variables. This is mostly owing to the lack of autonomous sensors that are stable over periods comparable to the servicing time of the moorings at the more remote locations. Several existing time series stations in key locations for carbon system and tracer investigations have been identified, and are listed below. Extension of the system to these locations is strongly dependent on the technology development in autonomous sensors. In addition, time-series sites and survey lines should be chosen to maximize the integration across the different components of the ocean carbon observing system including surface VOS lines.

Possible Additions	**Basin**
Station ‘W’ (40ºN, 70ºW)	North Atlantic
Northeast Atlantic (55ºN, 20ºW)	North Atlantic
Weddell Sea (63ºS, 50ºW)	Southern Ocean
North Pacific (30ºN, 135ºE)	North Pacific
Southeast Pacific (50ºS, 90ºW)	South Pacific
Station Mike (Nordic Seas)	North Atlantic
KNOT (Western North Pacific)	North Pacific
SEATS/South China Sea /Taiwan	North Pacific
KERFIX (South Indian Ocean)	South Indian
CARIAOCA (Southern Caribbean)	North Atlantic
BRAVO (Labrador Sea)	North Atlantic
Pacific Stations (0ºlat., 165º E, 140º W, 110º W)	Equatorial Pacific
Coastal Time Series (LTER sites, LEO-15, CALCOFI, MBARI)	North Atlantic, North Pacific
Sub-Antarctic Zone (47ºS 142ºE)	Southern Ocean
Central Arabian Sea	Indian
Central Bay of Bengal	Indian
PIRATA Mooring Array	South Atlantic

Research and Development -
With respect to time series observations, the Initial Observing System should:

1. Continue support for existing time-series stations and transition into a coordinated time-series network;
2. Add new time-series stations in key remote locations (high latitude water formation regions of N. Atlantic, Southern Ocean, ocean margin systems);
3. Deploy chemical and bio-optical instruments on moorings of opportunity (e.g. CLIVAR surface flux moorings);
4. Develop automated, in-situ techniques for measuring a suite of biogeochemical properties over appropriate spatial and temporal scales;
5. Investigate low cost mooring systems for deployment in remote regions.
6. Create new time-series stations cutting across a wide range of biogeographical, climate, and disturbance regimes, including coastal areas;

4.4 Satellite Remote Sensing

Application - Remote sensing provides us with the only global view of the oceans on synoptic timescales. For ocean carbon, remote sensing capabilities can be broken down into three main thematic categories:

- Quantifying upper ocean biomass and ocean primary productivity;
- Providing a synoptic link between the ocean ecosystem and physical processes;
- Quantifying air-sea CO_2 flux.

These issues can be addressed through a combination of remotely sensed parameters such as chlorophyll-a, chlorophyll fluorescence, light attenuation, pigment composition, coloured dissolved organic matter and DOC, and physical parameters such as wave state, wind speed, sea surface temperature, and mixing.

Since the early days of ocean-colour remote sensing with the Coastal Zone Color Scanner launched by NASA in 1978, significant advances have been made in understanding the optical properties of aquatic substances and their influences on ocean colour. In the most optically-simple systems of the open ocean, algorithms relating satellite data to surface ocean processes are typically constructed by calibrating changes in ocean colour against changes in concentrations of chlorophyll-a in surface waters. These simple algorithms have been remarkably successful in estimating chlorophyll from satellite data in many areas of the ocean. However, in more optically complex systems, these simple algorithms fail, and it has become clear that the relation between the concentrations of aquatic substances and ocean colour is complex and non-linear. Further, the geographic distribution and classification of "optically simple" (Case 1) versus "optically complex" (Case 2) systems are not fixed, and waters in a certain region may exhibit both simple and complex characteristics at various times. New algorithms are being developed to improve the success of retrievals, but much work remains to be done. The development of new algorithms depends on remote observations by sensors with increased capacity, complemented by appropriate in-situ observations and modeling to relate surface observations to the subsurface conditions and processes controlling the system.

The exchange of CO_2 between the atmosphere and the ocean is modulated by both physical and biological processes. The flux across the air-sea interface is driven by the concentration gradient and the gas exchange coefficient, which is a function of the sea state and wind speed at the interface. Photosynthesis by phytoplankton in the surface water decreases CO_2 at the surface by converting it into organic carbon, thereby increasing the concentration gradient between the atmosphere and the ocean. Some of this organic carbon then sinks out of the surface layers into the interior and deep ocean, where it is sequestered over long timescales. The gas exchange coefficient is typically parameterised as a function of the wind speed or wind friction velocity, or more recently, as a function of wave characteristics. Remote sensing can provide information on both the biological and physical processes controlling the exchange of CO_2, such as wind speed, wave characteristics (slope), sea surface temperature, and information on biological production from which changes in the surface CO_2 concentration may be inferred.

The majority of anthropogenic CO_2 uptake by the ocean, however, occurs through intermediate and deep-water formation processes. (See Section 6, Ocean Process Studies for more information). While remote sensing of physical oceanographic properties is in general far more prevalent than for chemical or biological variables, this section will not focus on the physical variables, as they have already been discussed in detail in the IGOS Ocean Theme.

Specific Applications of Remote Sensing of Ocean Carbon

Ocean colour remote sensing is undergoing a transition from research and proof-of-concept missions to operational missions, and operational data products and services from ocean colour are already being developed. The International Ocean-Colour Coordinating Group (IOCCG) was formed in 1996 to act as a liaison and communication channel between users, managers and agencies in the ocean colour arena. The reports of the IOCCG provide background information on ocean-colour, reviews of current research developments, and operational and planning information such as minimum requirements for operational ocean-colour sensors, and status and plans for satellite ocean-colour missions. This section draws heavily from ocean colour applications chapter of the IOCCG Report Number 3 (2000). Readers are referred to this document for further details (available on the IOCCG web-site: http://www.ioccg.org/ioccg.html). Listed below are those parameters that are directly applicable to ocean carbon cycle research, although it is acknowledged that other variables are often needed for corrections and optimisation.

Light attenuation and water colour – Phytoplankton and biologically-mediated chromophoric dissolved organic matter (CDOM) largely control the optical turbidity in large parts of the oceans, and thus strongly influence the heating of the mixed layer. This optical turbidity and light attenuation is a key component in physical mixing models of the surface ocean, and a strong determinant of the timing and magnitude of the stratification and erosion of the seasonal thermocline. These physical processes play a major role in both biological productivity (through the supply of nutrients) and air-sea gas exchange (through ventilation and mixing) that drive the ocean carbon cycle.

Chlorophyll fluorescence – Fluorescence measurements can be used to measure marine biomass, and in combination with chlorophyll-a measurements, fluorescence may be used as an indicator of phytoplankton physiological state.

Pigment composition and bloom type – Differences in pigment composition and reflectivity (backscatter) can be used to distinguish between some algal classes and pigment groups, such as the cyanobacterium *Trichodesmium sp*. and coccolithophorid species. Future ecosystem models will depend increasingly on information about the ecosystem community structure to be able to adequately reproduce the biogeochemical cycling of nutrients and carbon.

Water column primary production - Primary production by phytoplankton forms the basis of marine food webs and drives the biological pump for CO_2. Algorithms for estimating water column primary production rely on remotely sensed chlorophyll-a, light attenuation, and estimated surface irradiance. This computed production, however, is extremely sensitive to light attenuation by substances other than phytoplankton, and improvements to biomass algorithms are needed to help distinguish between biomass and other factors influencing the light attenuation. In addition, primary production algorithms must extrapolate from surface chlorophyll concentrations to vertical chlorophyll profiles, which requires in-situ data and / or an integrated approach coupling remotely sensed data with surface physical mixing models.

Benthic primary production – Using surface irradiance and attenuation coefficients to predict bottom light intensity along with plant biomass distribution information, it is possible to predict benthic primary production, which may play an important role in the total primary production in shallow coastal waters.

Yellow substances –CDOM can serve as a carbon source for production of inorganic carbon species. This CDOM is a coloured fraction of dissolved organic carbon (DOC), which plays a major role in the ocean carbon cycle. The largest land-to-ocean carbon flux is the riverine transport of DOC to the oceans, and CDOM has been shown to be a conservative tracer of riverine inputs in coastal waters. However, correlations between CDOM and DOC are not well established, and in many areas, there appears to be no direct correlation at all (Siegel, D., in press). In the open ocean, recent results from SeaWiFS demonstrate that the surface CDOM concentration undergoes a substantial seasonal cycle and thus is likely controlled primarily by local biological / chemical processes and upwelling of subsurface waters. Photochemical reactions with CDOM also produce a number of radiatively and chemically important species released to the atmosphere.

Gas transfer coefficient – The transfer of gases between the surface ocean and the atmosphere is a function of the concentration gradient of the gas across the interface and the gas transfer velocity, which is typically parameterised as a function of wind speed (or friction velocity). The gas transfer coefficient, however, has been shown to be much more strongly correlated with wave characteristics such as the wave slope than with wind speed, and there has been a growing trend towards utilizing scatterometry data to provide information directly related to the state of the sea surface. Algorithms relating gas transfer velocity to wave characteristics may significantly diminish the current 50% uncertainty in gas transfer velocity estimates obtained when wind speed alone is used.

There are many other applications of remote sensing for the study of biological and chemical processes in the surface oceans. We have only outlined here the major applications of direct impact to the ocean carbon cycle. Many of these applications are still in the research phase while others are already considered to be operational data products. Progress in algorithm development and data integration into models requires coordinated and complementary efforts in satellite missions and in-situ observations. An in-situ, global network of ocean carbon observations that is designed within the framework of available remote-sensing capabilities and resources will greatly improve algorithm and model development in a range of oceanic environments and conditions. These planning efforts for ocean carbon monitoring are currently being carried out by a number of international organizations such as JGOFS, IGBP, IOCCG, GOOS, IOC, and SCOR.

Coordinated Observational Requirements

As mentioned earlier, much of the activity in remote sensing for ocean biology and carbon is still in the research phase. The promise of remote sensing applications, however, has generated much enthusiasm in the ocean carbon cycle research community, and the transition from the research phase to an operational phase is on the horizon. The challenge for coordinated, complementary, and sustained programmes is great and must be addressed in the earliest planning stages of both the in-situ and remote sensing observation network.

Sampling Requirements / Methods – Remote-sensing requirements and plans for the Initial Observing System for ocean carbon over the next decade are being developed. The CEOS / WMO have compiled the observational requirements of the ocean, terrestrial, and atmosphere communities, as well as information on space agency missions and instruments (http://www.wmo.ch/ WMO satellite activities). The IGOS-P Ocean Theme report outlines the operational, approved, and planned / (pending approval) missions for ocean biology and surface carbon flux, of which ocean carbon cycle observation is a subset.

The general requirements for global ocean-colour observations are [IOCCG (1999)]:

i. Global spatial coverage at a resolution of 4-8 kilometres;
ii. Three to five day temporal resolution;
iii. A minimum band set that includes four channels in the visible and two in the near infrared with adequate spectral resolution and signal-to-noise ratio.

The IOCCG has recently developed a list of in-situ measurements required to support satellite ocean colour. (For further details, readers are referred to the IOCCG Report Number 3 (pg. 89) and the Ocean Optics Protocols, Table 2.1 of that report.)

1) ***In situ* Water-Column Measurements**

Samples to be collected through the water column down to the 1% light level

a) Minimum required measurements
- Chlorophyll-a (Fluorometric method)
- Phytoplankton pigment composition (HPLC method)
- Yellow substance absorption coefficient (CDOM)
- Total suspended particulate material (coastal waters)
- In-situ photosynthetic rates and parameters

b) Highly desired measurements
- Total particle, phytoplankton and non-pigmented particle absorption spectra
- DOC
- Optical measurements (ocean colour, spectral light transmission etc.)

2) **Semi-automated, underway measurements**
- In-vivo fluorescence (note: requires frequent calibration)
- Partial pressure of CO_2
- Nutrients (N, P, Si)
- Incoming solar radiation (PAR)
- Wind speed and direction
- Temperature
- Fast repetition rate fluorometry (FRRF) (ideally calibrated frequently against ^{14}C uptake measurements)

Existing System - As outlined in IOCCG (1999), OCTS, POLDER, SeaWiFS, MODIS-AM, MERIS, GLI, and MODIS-PM each fulfil the spatial and band set requirements. The temporal resolution of each instrument, however, is estimated to be at most 15% global ocean coverage per day. The IOCCG has recommended 60% global ocean coverage over a 3-5 day timeframe, requiring 3 satellites. Figure 6 of the IGOS Ocean Theme presents the timeline of current and planned ocean-colour missions from 1998 to 2012. In addition to the missions listed, there is the Taiwanese OCI sensor covering the sub-tropical latitudes, and the Korean OSMI sensor, which is a proof-of-concept global mission. These two sensors, however, do not include the two near-infrared bands for atmospheric correction as specified in the IOCCG requirements. With the series of missions outlined in the IGOS Ocean Theme, ocean colour observations should be met for the next decade or so.

Enhancements to the System - In terms of complementing remote sensing programmes, the time series stations and VOS / SOOP lines provide both temporal and spatial coverage of a suite of biological and carbon system properties with which remote sensing data may be integrated. As discussed in the technology development section, however, autonomous sensors for biological and chemical measurements are few, and at present, the existing sensors are often not suitable or practical for incorporation on platforms such as profiling floats or drifters. To take full advantage of the remote-sensing capabilities and to plan a coordinated observation network, there must be significant growth in the development of autonomous sensors for biological and chemical parameters. The IOCCG has outlined in-situ measurements required to support satellite ocean colour programmes, and many of the required measurements and measurement platforms are already operational. The challenge now is to coordinate the efforts of time series measurements and VOS sampling programmes to complement remote sensing programmes, and to encourage the technology development necessary to augment the system.

Research and Development - The link between remote sensing observations and ocean processes is algorithm development. The development of algorithms requires sensors with the appropriate number of channels, a minimum number of satellites flying these sensors to provide sufficient temporal and spatial coverage, and a quantitative understanding of in-situ ocean processes. These needs must be met through a combination of smaller scale process studies, dedicated and routine measurements at appropriate locations, and model development. These challenges are more fully described in this document in the sections on numerical modeling, technology development, and process studies. Clearly, the components of such a coordinated, operational system must be developed initially in parallel with a view towards optimisation in time as the science and technology develops.

4.5 Coastal Ocean and Margins Studies

Application - The objectives for a coastal observing component may be grouped into a series of related topics requiring the following:

- Quantification of the interfacial exchanges with the coastal zone (rivers and estuaries, atmospheric deposition and air-sea exchange, sediment-water exchange, and groundwater inflow)
- Determination of the fate of organic and inorganic carbon entering the coastal system
- Calculation of the rates of biogeochemical cycling in the near-shore, shelf, and slope environments
- Calculation of the large-scale effect of coastal open-ocean exchange, and characterization of the sensitivity of coastal/margin processes to human and climate perturbations (to include terrestrial changes propagating in laterally).

Methods - The observational requirements for coastal and ocean margins regions are challenging, in part because of the complexity of the ecological and biogeochemical processes and the high spatial and temporal heterogeneity. In general, there has been a lack of a concerted effort to collect, on a global scale, observational data dealing with air-sea CO_2 exchange in coastal and margin systems, and the importance of these areas for the "solubility pump" remain largely unquantified. In addition, because of high rates of primary production, carbon burial in shallow deposition areas and deltas, and export to the deep ocean, the “coastal biological pump” exerts a significant influence on local surface pCO_2 levels and through lateral exchange may impact air-sea CO_2 exchange in open ocean areas. Several investigators have tried to use limited data to evaluate the role of the coastal zone in the global carbon cycle. Because of the accumulation of $CaCO_3$ in coastal zone sediments and the net imbalance between gross productivity and gross respiration, the global coastal zone seems to have been a net source of CO_2 to the atmosphere before extensive human interference in the system – certainly the proximal coastal zone has been a source. It must be noted, however, that because of the exclusion of benthic primary production and other methodological limitations, there exists some doubt about the hypothesis that there was, in fact, a net imbalance between gross productivity and gross respiration. If this imbalance did exist, today there may be cause for concern - as CO_2 has built up in the atmosphere, the tendency for CO_2 to invade coastal waters has become important. Some modeling studies have suggested that early in this century the "back pressure" induced by the build-up of CO_2 in the atmosphere will become great enough to overcome the CO_2 out-flux and atmospheric CO_2 will invade coastal waters on a global scale. These conclusions are controversial and open to debate, in part because there has not been a good global observational program for coastal waters.

New evidence from the Baltic Sea, the East China Sea, and the Mid-Atlantic Bight, where there are considerable riverine inputs of carbon, all demonstrate that they are net sinks of atmospheric CO_2. The possible mechanisms include active biological uptake of CO_2 in the summer, high CO_2 solubility in the winter, and effective shelf transport and shelf-edge export processes of particulate and dissolved carbon species, otherwise referred to as the "continental shelf pump". In the coastal upwelling areas, new studies show juxtaposition of sources and sinks of CO_2, which are associated with phytoplankton populations that appear to be controlled by the iron fluxes released from the adjacent shelves.

While the evidence is extremely limited, the initial consensus seems to be that the effect of the solubility pump in the continental shelf area can be extremely active, but still may be quite small relative to global totals. This does not, however, seem to be the case for the biological pump operating in the coastal zone. For biologically mediated processes to be important on climate scales, carbon must be transported below the winter mixed layer – any shallower than this and the carbon is available to re-equilibrate with the atmosphere the following year, which is too short for climate relevance. Thus, while it may be claimed that the open ocean accounts for the majority of the primary production and even export production, the continental margins and equatorial regions account for approximately half of the organic carbon rain that reaches the deep ocean and margin sediments below the zone of rapid remineralisation. Additionally, processes in margin systems, such as denitrifications and iron inputs, exert major controls on nutrient distributions that control the biological pump even in the open ocean. For these reasons, the ocean margin regions could represent approximately half of the important fluxes and more than half of the present uncertainty in assessing the factors that control the biological pump globally. These areas must be made a high priority for research and monitoring.

The Existing System – While there are certainly coastal time series stations that measure carbon system variables, VOS that measure pCO_2 in coastal areas, and satellite coverage over these areas, there does not exist an inventory of these observing system elements to describe an initial continental margin carbon observation system. There are several international and intergovernmental groups currently working to provide the necessary information – the Coastal Ocean Observing Programme of the IOC, IGBP's Land-Ocean Interactions in the Coastal Zone (LOICZ) project, and the IOC / LOICZ/ JGOFS Continental Margins Task Team.

Enhancements to the System - A long-term observing network for coastal zones and ocean margins needs to be established. The time and space sampling requirements differ from the open ocean, and the optimal design will likely require emphasis on numerous low intensity time-series and remote sensors. Further, directed in-situ observations are needed to estimate:

- the transport of organic and inorganic carbon via rivers and groundwater;
- riverine, atmospheric, benthic, and groundwater sources of nutrients that affect biological carbon cycling in the coastal zone;
- exchanges with sediments along the continental margins;
- exchanges between the continental margin, and the open ocean.

These studies should aim to improve satellite algorithms for, and numerical model parameterization of, coastal and ocean margin processes, and should be conducted in a manner that is fully integrated and coordinated with basin-scale surveys and process studies.

Research and Development -
With respect to coastal issues, the Initial Observing System should:

1. Complete synthesis of historical data on coastal and ocean margins;
2. Coordinate existing national coastal observational capabilities including compiling and distributing data sets;
3. Implement network of coastal observing systems that are a combination of spatial surveys and time-series;
4. Monitor the riverine and atmospheric inputs of carbon and nutrients to the coastal region;
5. Develop a set of coastal/margin process studies to address key unknowns (e.g. ground water inflow; open-ocean exchange);
6. Foster more vigorous interaction among terrestrial, coastal and open-ocean research communities.
7. Develop automated, in-situ techniques for measuring biogeochemical properties over appropriate timescales.

4.6 Atmospheric Monitoring

Exchanges between the atmosphere and the ocean significantly affect both marine and atmospheric biogeochemical cycles of key nutrients and gases. These linked processes must be characterized and quantified in order to fully understand and eventually predict the behaviour of the carbon system.

The atmospheric distributions and variations of a number of chemical species carry important information on oceanic processes:

1. CO_2, carbon isotopes and O_2/N_2 ratios - There is an extensive network of atmospheric measurements of greenhouse gases as well as a global data integration project (GLOBALVIEW-CO_2) that provide data for modeling and flux estimations. The initial global atmospheric network focuses on measurements in the remote marine boundary layer to avoid contamination by local sources and sinks, but recent efforts have involved expanding the network into continental interiors. Global atmospheric models of CO_2, however, often disagree with ocean models about the location and strength of ocean uptake of CO_2, especially in the Southern Ocean. Atmospheric measurements can provide global and / or hemispheric estimates of the seasonal and interannual variability in ocean uptake, but rapid atmospheric mixing rates make it difficult to evaluate regional sources and sinks. Ocean carbon measurements provide the most direct estimate of air-sea CO_2 fluxes and, with an appropriate sampling strategy, can provide information on a wide range of time and space scales. The discrepancies between atmospheric and ocean model estimates of ocean CO_2 uptake should be used to determine where more data are needed and how to best optimise both the atmospheric monitoring and ocean monitoring systems. In addition to CO_2, the observing system should include measurements of $\delta^{13}C$ and $\delta^{18}O$ in CO_2, CO, and the O_2/N_2 ratio. These measurements are used for deducing the mechanisms responsible for fluxes in inverse modeling: $\delta^{13}C$ and O_2/N_2 are used to distinguish terrestrial from air-sea exchange, O_2/N_2 can provide direct insight into changes in the net productivity of the global oceans, $\delta^{18}O$ is used to estimate gross primary production (as opposed to net ecosystem exchange), and CO is used to estimate the contribution of combustion. However, because of potential ambiguities in atmospheric O_2/N_2 (e.g., due to subsurface warming or changes in ocean circulation), additional oceanic oxygen measurements may be required. A comprehensive observational program should include all of these approaches as they can be used to validate each other and the climate models used to predict future uptake rates.

   With the advent of satellite based CO2 estimates and other near autonomous CO2 measurements coming on-line over the next several years, there will be a growing effort to provide data in near-real time (weeks to a few months) for data assimilation / hindcast programs. The World Data Centre for Greenhouse Gases (WDCGG), part of the Global Atmosphere Watch (GAW) programme, was established in the Japan Meteorological Agency (JMA) in October 1990 to make systematic collection and distribution of the data on the concentrations of greenhouse gases (CO_2, CH_4, CFCs, N_2O, etc.) and the related gases (e.g., CO, NOx, SO_2) in the atmosphere and the ocean. JMA provides monthly CO_2 mapping and flux estimates based on observations, and provides some observational data through the WDCGG. However, not all the data are available in near real time by all contributing institutions. Within this programme, mechanisms should be developed to ensure the rapid exchange of CO_2 observations.

   Efforts are underway by a number of groups to develop a satellite remote sensing capability for atmospheric CO_2. Several technologies are being pursued (passive thermal IR, passive reflected solar IR, and active lidar) that will likely provide beginning in summer 2001 column integrated CO_2 and in the future some vertical resolution. A number of serious issues remain to be resolved such as biases for covariances with water vapour and temperature. However, even the relatively low resolution suggested at the moment (2-4 µatm) can, with enough time/space sampling, improve on atmospheric inversions with surface data alone.

2. Atmospheric inversion models – The global atmospheric network provides important constraints on the spatial patterns of atmospheric CO_2 (e.g., inter-hemispheric gradient; zonal gradients in the Northern Hemisphere) and other biogeochemical tracers. However, to fully realize the potential of this data, information on atmospheric circulation must be incorporated, often in the form of an atmospheric tracer transport model. One of the more common uses has been inversion models where the global network data are used to estimate regional net fluxes on time scales of monthly up to interannual. At present, significant disagreements exist among models and between atmospheric inversions and in situ based estimates, a primary example being in the Southern Ocean where the data suggest a larger net CO_2 sink than do the atmospheric models. An important goal of an ocean carbon observing system is to provide independent estimates of the air-sea CO_2 fluxes (time/space patterns) for comparison with and incorporation into inversion studies.

3. Dust (trace metals), nutrient deposition, and dimethylsulfide - In specific regions, the marine biota may be expected to respond to input of nutrients from the atmosphere, in particular, iron from dust in iron-poor regions, and nitrogen inputs in nitrogen-limited regions. Changes are likely in these inputs in the next century owing to anthropogenic effects. Of particular concern are inputs of nitrogen from the developing economies in Asia, affecting the western Pacific and North Indian Oceans, and industrial development in currently pristine regions of the Southern Hemisphere. In addition, the increased biological productivity resulting from iron and nutrient inputs leads to the increased production of dimethylsulfide in the surface ocean. It is believed that cloud albedo may be substantially influenced by marine sulphur emissions through the formation of sulphate aerosol particles and cloud condensation nuclei. This is potentially a very important feedback mechanism on a 50-100 year timescale.

4. Meteorological forcing – In a changing climate and with changing land-use patterns, regional winds may change significantly or increase in intensity. This would be expected to increase the prevalence of nutrient-rich ecosystems at the expense of steady-state ecosystems, for example by increasing the rates of coastal upwelling and open-ocean mixing. Aeolian deposition of iron and nutrients and the concomitant changes these inputs have on surface productivity would also be driven by wind patterns and strength.

Atmospheric monitoring of these and other chemical species and forcing mechanisms are necessary to place constraints on ocean processes and to understand and quantify the integrated atmosphere-land-ocean carbon system. The observational network must be designed carefully and in collaboration with experts from all three fields to optimise the location and frequency of measurements. Additionally, these monitoring activities should make full use of the anticipated remote-sensing data and new measurement technologies.

4.7 Numerical Modeling

Despite near-term advances in in-situ measurements and remote sensing, ocean carbon observations alone will almost certainly remain too sparse to fully characterize the relevant time-space variability of the marine carbon cycle and the net air-sea carbon fluxes with the atmosphere. Diagnostic modeling (inverse models up to full data assimilation systems) provides a means to generate complete, dynamically consistent ocean carbon fields that incorporate data when and where they are available, and that give rigorous estimates of uncertainties on the inferred quantities. These model-generated products provide the input needed for scientific and political assessments of the state of the ocean and its role in the global carbon cycle. These products can also provide initial conditions for short-term and long-term predictions using prognostic models. Inverse models also offer a formal method for designing optimal observational networks, evaluating the quality of observational data, assessing the adequacy of model parameterizations and parameter sets, and investigating the overall quality of model structure.

Diagnostic modeling therefore provides a natural framework for integrating the different elements of ocean carbon cycle research: in-situ observations, satellite remote sensing, process studies and prognostic modeling. The two main components of the proposed diagnostic modeling framework are ocean carbon data centres and the ocean carbon data assimilation systems. The ocean carbon data centres 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 centres 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 centres need to be established and supported. The data synthesis efforts at these data centres should also include quality control procedures that extend beyond the initial quality control done at the level of the individual observations. This includes, for example, investigation of the internal consistency of the data as well as testing for long-term precision and accuracy of the data. High priority should also be given to fully documenting the various data products and streams (metadata).

Diagnostic mathematical methods have only very recently begun to be used in global carbon-cycle research. These models can range in their spatial coverage from regional to global and can be of various complexity in both their mathematical approach as well as in their biogeochemical representation. The main products will be an optimal estimation of the current sources and sinks of CO_2 in the ocean and of the state of the ocean carbon cycle in general (e.g. primary productivity). Three main groups of users can be identified: the oceanographic, atmospheric and terrestrial research community; the scientific assessment and policy communities; and commercial fisheries and fishery managers. However, at present, availability of existing expertise and experience to judge which method to apply to a particular biogeochemical problem is scarce. It is therefore imperative that resources be allocated to develop and test different schemes on a variety of temporal and spatial scales, making use of a large variety of data. The exact nature and structure of an ocean carbon diagnostic modeling framework is an open question that requires fundamental research.

Data assimilation in physical oceanography, while not as advanced as in the weather forecasting community, has made significant progress over the last several years. Several programs have been initiated at the international level such as GODAE (Global Ocean Data Assimilation Experiment; http://www.bom.gov.au/bmrc/mrlr/nrs/oopc/godae/homepage.html) and at national levels, e.g. ECCO (Estimating the Circulation and Climate of the Ocean; http://www.ecco.ucsd.edu) within the United States or MERCATOR in France. The fundamental objective of GODAE is a practical demonstration of real-time global ocean data assimilation in order to provide a regular complete depiction of the ocean state at time scales of a few days, space scales of several tens of kilometres, 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.

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

With respect to modeling needs, the Initial Observing System should:

1. Initiate pilot studies that investigate the methods, data needs, and general feasibility of a carbon data assimilation system;
2. Implement preliminary ocean carbon data centres to coordinate the compilation, quality control and distribution of in-situ, remote sensing, and atmospheric data relevant to the ocean carbon cycle;
3. Foster linkages with the developing ocean climate data assimilation efforts;
4. Maintain a vigorous development and model-data evaluation effort for prognostic ocean carbon and biogeochemistry models;
5. Expand the IGBP-GAIM OCMIP intercomparison effort into ecosystem modeling and interannual to decadal variability.
6. Improve / develop representations of ocean margin processes.

Summary

This section outlined the basic elements of a carbon observing system and the existing and planned programmes that may form the basis of a global carbon observation system. While we may still be some distance from achieving global coverage, we are well within reach of having pilot, basin-wide observational systems. To meet the scientific objectives of a carbon observing system, truly global coverage is not immediately required in order to obtain globally significant results. A basin-scale pilot programme consisting of a number of VOS lines, fixed-point time-series from moorings and servicing ships, a number of repeat hydrographic sections, and coastal observations from ferries, could be realized in the North Atlantic in the next few years using existing infrastructure and cooperation between the Europeans, USA, and Canada, and in collaboration with a number of programmes such as CLIVAR, SOLAS, and ANIMATE.

5. Technology Development

For those quantities that cannot be resolved from space, directed technological development is needed on autonomous in-situ sensors, samplers and platforms. Particularly promising directions for in-situ sampling over the near-term future (3-10 years) include new autonomous chemical and biological sensors (e.g. pCO_2, DIC, nutrients, particulate inorganic carbon, bio-optics) and ocean platforms (e.g. drifters, moorings, profiling floats, gliders, and AUVs). There are, however, several important constraints and limitations for employing existing autonomous sensors on ocean platforms. For example, the size and weight of the pCO_2 systems now available may be too great for most profiling floats, autonomous underwater vehicles, and gliders. In addition, these platforms are often used for missions to 2000m depth, far in excess of the near surface and surface system design of the present pCO_2 sensors. One of the most serious limitations is the data collecting capability of approximately 6-12 months, limited by biofouling, sensor stability, and in some cases, reagents. This timeframe is much shorter than the lifetime or turn-around time of the platforms, and thus deployment on these long-term missions is not practical. The need to recover instrumentation for periodic or post-calibration must be factored into the development of the observing system. Platform strategies for sampling chemical species including CO_2 have been reviewed by Merlivat and Vezina (1992) and more recently by Tokar and Dickey (2000) and plans for global observations using a multi-platform approach have been described by Send et al. (1999) and Griffiths et al. (1999).

Although the central focus is on pCO_2 measurements, it is important to take a broader view of the observational needs to quantify, understand, model, and predict CO_2 variability of the atmosphere-ocean system. Complementary measurements of meteorological variables are often needed, especially to determine air-sea fluxes of CO_2. Similarly, a suite of in-situ chemical, bio-optical, and physical measurements are needed to quantify the roles of the "biological and solubility pumps." In some cases, proxies for these processes can be determined from satellite observations. However, in many areas satellite coverage is not continuous or space-borne sensors may respond to surface processes only. In designing the pCO_2 sampling program, it will be important to include key interdisciplinary variables that can be sampled concurrently. Progress is being made for measuring micro- and macro-nutrients (e.g., review by Blain et al., 2000; Dickey et al., 1999, 2000a,b; McGillicuddy et al., 1998; McNeil et al., 1999). Platforms capable of multi-variable sampling will be especially effective (e.g., Tokar and Dickey, 2000).

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. Recently, a Japanese system has been developed 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.

Moored Buoys **-** Moorings are the most mature technology available to support autonomous CO_2 measurements. The oceanographic community has extensive experience supporting these platforms. Several systems are being developed for measuring pCO_2 autonomously. 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.

Drifters - Drifter technology was widely used in support of the WOCE program, albeit with a limited sensor suite (often temperature only). Drifters do not provide information on the ocean interior (quite limited for meteorology), but they may provide a unique Lagrangian perspective on biogeochemical processes. Surface drifters equipped with the 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. However, some work in this area has been done with the CARIOCA buoys (Hood et al., 1999; Bakker et al., 2000 *in press*; Hood et al., 2001a,b), demonstrating the feasibility of such an approach.

Profiling Floats **–** The *Argo* programme will deploy some 3000 profiling PALACE-type floats to monitor temperature and salinity in the ocean interior. The *Argo* floats are targeted for ~4 year endurance with ~100 vertical profiles to 2000 m every 10 days. The floats are not recovered after deployment. These platforms have become a practical alternative for exploring the vertical distribution of properties in the ocean. As mentioned before, there are several limitations for using CO_2 sensors on profiling floats, including the current 6-12 month endurance of CO_2 sensors and size limitations. Compact chemical sensor suites suitable for monitoring biogeochemical properties are the primary limitation to use of float technology to monitor carbon system parameters. However, in-situ CO_2 (e.g., SAMI CO_2; DeGrandpre et al., 1995; 2000) and colorimetric pH sensors (Kaltenbacker et al., *in press*; Hopkins et al., *in press*) with many of the required characteristics have been demonstrated. It is reasonable to assume that floats with the required sensors could be developed, although it would be a much greater challenge to extend sensor lifetime to the 4 to 5 year endurance that would match the *Argo* platform capabilities. It might be more reasonable to operate biogeochemical floats at a higher profile rate, and shorter lifetime that was matched to sensor endurance. The lifetime was assumed to be double the assumed endurance of surface drifters, which are exposed to continuous biofouling and surface waves.

Gliders - Gliders are essentially steerable profiling floats. They are, however, the most difficult platform on which to integrate biogeochemical sensors due to their relatively small volume and the faired design that is required to maintain hydrodynamic performance.

Autonomous Underwater Vehicles - The potential application of AUV technology would be best suited for high-resolution studies of smaller ocean areas rather than sustained monitoring activities.

6. Ocean Process Studies

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

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

The 1990s saw an extensive array of upper ocean biogeochemical process studies conducted under JGOFS and other programs in the North Atlantic, Southern Ocean, Equatorial Pacific, North Pacific, and Arabian Sea. The focus of these field projects, although multi-faceted, can broadly be categorized as the mechanisms controlling primary production, surface pCO_2, and carbon export flux. Recently, a number of meetings of the international ocean carbon research community have been held to discuss future directions and priorities for research and monitoring programmes. The process studies being discussed focus on understanding the ocean's role in global climate change and how ocean biogeochemical processes may be affected by a changing environment. In addition, the planning for these studies is being developed within the framework of the developing observation system. Details of these planning activities and process studies can be found in the JGOFS EC-US Ocean Carbon Workshop reports (Ducklow et al., in press). What we present here is a brief description of the process studies being discussed by the international ocean carbon research community. Readers are referred to the JGOFS reports for complete details.

Ocean Physics - To a large degree, the long-term oceanic uptake of anthropogenic CO_2 is controlled by water mass transport. The Ocean Carbon Cycle Model Intercomparison Project (OCMIP 1 and 2) has demonstrated that improved knowledge of ocean circulation processes would, more than any other single factor, improve our ability to predict the behaviour and magnitude of the ocean carbon sink. The majority of anthropogenic CO_2 penetration into the ocean occurs as a result of themohaline ventilation and thermohaline circulation. However, though the circulation itself is large in scale, the mixing processes that determine its rate occur on scales too small to be resolved explicitly by models today or in the foreseeable future. The main process studies should focus on exchange across the base of the winter mixed layer, diapycnal mixing, deep convection, and deep-water overflow entrainment. The key problems for further research are:

- Investigations of the turbulence regimes in different parts of the ocean;
- Studies of convection and its forcing;
- Studies of cross-frontal mixing.

Air-Sea Gas Exchange – The relatively small net annual CO_2 uptake resulting from the rise in anthropogenic atmospheric CO_2 is superimposed on much larger seasonal variations in surface CO_2 resulting from seasonal warming and cooling, photosynthetic activity, and upwelling. As a result of these large temporal and spatial variations, different regions of the world's oceans may display under- or over-saturations with respect to atmospheric CO_2 concentrations and may serve as both source and sink of atmospheric CO_2 at various times throughout an annual cycle. However, because the strength and duration of these sink and source periods varies, many areas act as net annual sinks or sources when averaged over the full year. Along with air-sea concentration differences, the rate of exchange of gas between the ocean and atmosphere depends strongly on the gas exchange coefficient, which is a function of the sea state. This relationship, however, is far from straightforward and difficult to measure directly, and the uncertainty on air-sea gas exchange estimates is approximately 50%. The main process studies must focus on providing a description of the contemporary geographical and temporal structure and variation of air-sea CO_2 flux as well as mechanistic understanding of surface layer processes that determine this flux both now and in the future. The key problems for further research are:

- Development of measurement techniques of flux on the same timescales as the variability in the environmental forcing;
- Determination of the ΔpCO_2 between the surface skin and the above-lying atmosphere in order to determine the gas exchange coefficient accurately;
- Validation of the measurements with conventional approaches;
- Correlation of the measurements of the gas exchange coefficient with wind speed;
- Determination of whether there are better or additional parameters than wind speed to parameterise the gas exchange coefficient in the field;
- Scaling up of results to global scale through remote sensing.

Biogeochemical Cycling **–** Biological processes lead to the formation of dissolved and particulate organic carbon in the surface ocean. Mixing, advection, and sinking particles transport this carbon from the surface ocean into the interior and deep ocean. Most of the organic matter reaching the deep ocean is subsequently remineralised back to DIC and inorganic nutrients, and the resulting metabolic DIC is sequestered from the atmosphere on a time-scale set by the deep-water circulation – several hundreds to a thousand years. A very small fraction of the sinking organic matter flux is buried in the sediments and thus removed from the system over geological time-scales. This process leads to a draw down of surface CO_2 concentrations, which in turn can drive a net air-sea CO_2 flux into the ocean. Over seasonal to annual time-scales, the surface ocean pCO_2 concentration varies as a result of the interaction among the seasonal thermal cycle, net community production / respiration, and subsurface mixing, which typically brings up colder water with high metabolic DIC concentrations. The dominant process varies by region, with typically stronger relative thermal driving in the subtropics (maximum pCO_2 in summer) and stronger biological and mixing processes in the sub-polar and polar regions (maximum pCO_2 in the winter).

The efficiency of the "biological pump" in relation to other mechanisms, however, remains largely unquantified, and the interdependencies between CO_2 transport and ecosystem dynamics, community structure, and nutrient availability are not fully understood. In considering how potential marine biological responses to climate could change the growth rate of atmospheric CO_2, the main foci are on processes that can decouple dissolved nutrients and DIC and/or can alter surface alkalinity. Climate change scenarios suggest consistent patterns of lower ocean pH, higher SST and enhanced near-surface stratification over the next century. Process studies coupled with long-term satellite remote sensing and autonomous in-situ measurements are needed to understand and quantify the seasonal cycle and interannual variability. The responses to natural perturbations (e.g. ENSO, dust events) are particularly important with regard to climate projection. Specifically, process studies must focus on major geochemical functional groups (nitrogen fixers, calcifiers, etc), iron limitation and micronutrients, dissolved organic matter, and Redfield versus non-Redfield stoichiometry of organic fluxes. The key problems for further research in both open-ocean and ocean boundary environments are:

- What is the strength of the biological pump and how does it differ among biogeographical provinces? How do we most accurately measure its strength?
- How does the structure and composition of the biological pump change in space and time? How might community structure affect it, and what is the importance of selected functional groups (e.g., nitrifiers, diatoms, calcifiers, large grazers)? What are the relative roles of the microbial and zooplankton communities in enhancing/retarding pump strength?
- What is the sensitivity of the biological pump to perturbations in forcing (upwelling, dust and Fe deposition, North Atlantic Oscillation, El Niño)? How do we quantify this variability (e.g., time series).
- How will the biota respond to warming, chemical changes (DIC, pH), and physical changes to the habitat such as enhanced stratification?
- What are the important processes (N_2 fixation, Fe limitation, etc.) that prevent a simple relationship between net or total production of ecosystems and the macronutrient concentrations of the ambient waters?
- What processes cause the C/N/P ratio of organic matter produced in the euphotic zone to vary ? How is this linked to plankton community structure ? How does the elemental composition of the material remineralised in the underlying *twilight zone* differ from the source material, and how do biological processes such as bacterial consumption, active planktonic transport, particle dynamics, and "repackaging" affect this differential remineralisation ?
- How does the ratio of net/gross production in the euphotic zone depend on sea surface temperature and stability?
- What are the time and space varying processes in the mesopelagic zone (100 to 1000 m) that control the recycling and gravitational flux of carbon?

The JGOFS reports also recommend a series of basin-scale studies to constrain estimates of carbon storage in the Northern Hemisphere and to determine the role of the ocean carbon cycle in amplifying or ameliorating the variation of natural and anthropogenic atmospheric CO_2, and thus climate change. The Northern Hemisphere oceans and the Southern Ocean figure most prominently in these recommendations, as do ocean margins – a previously unresolved but potentially very important component of the total ocean carbon system. These recommendations for basin-scale observations are developed within the framework of the developing observing system, taking advantage of ongoing observation strategies and proposing new observation programmes that would be suitable for addressing research needs. These types of recommendations are essential for optimisation of the observing system to answer unresolved questions about when, where, why, and how frequently to monitor certain variables to quantify the ocean's role and response to a changing environment.

7. Summary

The process of developing a plan and strategy for an ocean carbon observation system includes:

- Identifying core variables and requirements based on research objectives and priorities;
- Creating an inventory of existing operational measurements of these variables;
- Identifying the gaps in the existing system;
- Establishing priorities and methods for reducing the gaps;
- Enabling research needed to address scientific objectives and optimise the observing system; and,
- Encouraging the needed technology development.

This report is a first attempt at providing the background information needed to develop such a plan and strategy. While automated measurement techniques for carbon system variables are in their infancy, there are several proven and robust techniques that can at this time serve as the basis of the initial system – pCO_2 measurements on VOS, time series and buoy measurements of carbon system variables, and satellite remote sensing. The next steps include augmenting and refining the inventory of existing programmes (especially to include a more detailed inventory of existing programmes in ocean boundary environments), and establishing community consensus on the gaps in the system and on the priorities for system enhancement. Table 1 below summarizes the core variables and requirements needed to address scientific objectives, and Table 2 outlines the existing and planned operational systems. It must be stressed that at this stage of development, there must be a strong synergy between research programmes funded for a finite period and observing system elements that will be in place indefinitely. There are a number of international programmes whose research objectives closely match the research needs for the development and enhancement of the ocean carbon observing system, and a close alliance with these programmes is crucial.

Table 1. Requirements for Ocean Carbon Observing and Ancillary Measurements

Platform / Variable	Application	Horizontal Resolution	Vertical Resolution	Time Resolution
Ships – VOS/ SOOP • pCO_2 • Carbonate System • Ocean Colour Variables • Meteorological Observations • Vessel-mounted ADCP	Basin-scale air-sea flux and surface variability	Optimal: continuous along transects; Minimum: 50-100 km	Surface	Monthly to Seasonally
Ships – Hydrographic Surveys • pCO_2 • Carbonate System • Hydrography • Tracers • Meteorological Observations • Vessel-mounted ADCP	Large-scale inventories	WOCE Hydrographic Program (WHP) standard spacing; 30-50 km along section; More dense sampling on continental shelf	Full Water Column	5-10 year
Moored Buoys (Time Series) • pCO_2 • Carbonate System • Ocean Colour Variables • Ancillary physical, meteorological, chemical, and biological measurements	Temporal variability; high-frequency to interannual	Fixed – point (Eulerian) moorings or revisited stations located in strategic areas.	Selected levels distributed over full water column	Hourly to Monthly

Drifters • pCO_2 • Carbonate System • Ocean colour variables • Meteorological Observations • Surface currents and temperature	High frequency mesoscale to regional variability	Lagrangian (non-fixed point) on a regional or mesoscale	Surface	Hourly to Monthly
Satellites • Ocean colour signal • Ancillary data for air-sea flux estimates (eg, Wind, SST, surface current variability)	Basin-scale surface biomass productivity; phytoplankton natural fluorescence	Global spatial coverage, 4-8 km Coastal regions, 0.5 – 2 km	Surface	Daily to Weekly
Atmospheric Monitoring • CO_2 • $d^{13}C$, CO, O_2/N_2, $d^{18}O$, trace metals, nutrient deposition, DMS	Basin-scale air-sea fluxes and atmospheric transport	As available; 2-5º spacing.	Surface	Monthly to Seasonal

Modeling	***Application and Resolution***
Diagnostic models – inverse and data assimilation models	• generate carbon system and biogeochemical fields that incorporate available data • interpolate observations in space and time • estimate biogeochemical rates • optimal estimation of the current sources and sinks of CO_2 • initial conditions for prognostic models • formal method for designing optimal observation networks. Required on a wide range of time and space scales, and with varying degrees of complexity of ecosystem biogeochemistry parameterization.
Prognostic models - Global ocean climate models and coupled ocean-atmosphere models	• long integrations to examine the base state of the marine carbon cycle, natural interannual to geological variability, and climate change responses and feedbacks
High-resolution mesoscale basin-to-global models	• process studies of biological / physical / chemical interactions Required resolution – approximately 0.1° or less to be eddy – resolving
Coastal / Regional models	• process studies of biogeochemistry dynamics • range of carbonate system, biogeochemistry, and ecosystem components, depending on application

Notes:

Carbonate system includes: pCO_2, DIC, Alkalinity, and pH.

Ocean colour variables include: Chlorophyll-a, fluorescence, CDOM, and upwelled radiances at satellite wavelengths.

Hydrography includes: T,S, O_2, Nutrients, DOM, trace metals

Tracers include: Radiocarbon, d ^{13}C, Tritium-Helium-3, Halocarbons / CFCs

Accuracies : (note: for accuracies on hydrographic measurements, see OOPC climate observing system report)

pCO_2 minimum 3 µatm; optimal 1 µatm.

Chlorophyll-a 5-10% precision

DIC minimum 1-2 µmol/kg

Fluorescence 1-2 units

DOC 1.5-2% precision (about 1µmol / kg)

DOM DOC ˜ ± 2%; DON ˜ ± 4%

Alk minimum 2-3 µmol / kg

pH 0.0005 pH units

Table 2. Existing and Planned System Elements

VOS and SOOP Lines

Operational	Basin
TAO servicing ship	Equatorial Pacific
OISO servicing ship (Kerguelen Island – Crozet – Amsterdam Islands)	Southern Ocean
Alligator Hope (Tokyo – Vancouver)	North Pacific Transect
Alligator Liberty (Yokohama – Panama)	North Pacific – Central Pacific Transect
Atlantic Meridional Transects (UK – Antarctica)	Atlantic Meridional transect
Hesperides	North Atlantic
Line 'P' (Labrador Sea)	North Atlantic
Polarstern	North Atlantic, Pole to Pole
CAVASOO Programme (EU)	North Atlantic
Continuous Plankton Recorder	North Atlantic

Planned	Basin
Denmark – West Greenland	North Atlantic
Hamburg – Halifax	North Atlantic transect
UK – Jamaica or Miami	North Atlantic transect
GeP&Co (Le Havre – Nouméa)	North Atlantic, Caribbean, South Pacific
Hong Kong-Mexico (Manzanillo)	North Pacific transect
Peru (Callao)-Japan (Yokohama), west-bound, by NIES/JAMSTEC	North Pacific transect

Hydrographic Sections

Operational	Basin
Eastern Indian Ocean I10, I5E, 95ºE from 9ºS to 32ºS	Indian
48ºN Transect , BSH Hamburg and IfM-Kiel (WOCE Line A2)	North Atlantic
Labrador Sea, BIO, (WOCE line AR7W)	North Atlantic

Planned	Basin
SR3 Southern Ocean , Hobart to Antarctica along 140ºE	Southern Ocean (Pacific Sector)
P15S from 50ºS to Equator	South Pacific
JAMSTEC plans to occupy one Pacific hydrographic section every two years; first target is P17 and next is P3. Survey includes full CO_2 and tracer measurements	Pacific Meridional transect (P17) and North Pacific (P3)

Time Series Stations (ship and mooring based)

Operational	Basin
HOT (Hawaii) *ship-based and mooring-based*	North Pacific
BATS (Bermuda) *ship-based and mooring-based*	North Atlantic
Ocean Station 'P' (North Pacific) *ship-based*	North Pacific
ESTOC (Eastern Subtropical North Atlantic) *ship-based and mooring-based*	North Atlantic
KNOT (44°N, 155°E), operational from 1998-2000	North Pacific
TAO Array (Carbon sensors operated by MBARI and PMEL) *mooring-based*	Equatorial Pacific

Funded (February 2001)	**Basin**
Northeast Atlantic, Porcupine Abyssal Plain – *mooring deployment*, IfM Kiel and partners in the UK (ANIMATE)	North Atlantic
ESTOC - *mooring deployment*, IfM Kiel and partners in Spain (ANIMATE)	North Atlantic
Irminger Sea - *mooring deployment*, IfM Kiel and partners in Iceland (ANIMATE)	North Atlantic

Satellites Measuring Ocean Colour *(see IGOS Ocean Theme Figure 6 and Appendix 1 for details)*
The IOCCG has recommended 60% global ocean coverage over a 3-5 day timeframe, requiring 3 satellites. With the series of missions outlined in the IGOS Ocean Theme, ocean colour observations should be met for the next decade or so.

Existing (in orbit)	**Planned (approved or pending approval)**
MOS/IRS-P3	HY-1
SEAWIFS / SEASTAR	MERIS/ENVISAT
OCM/IRS-P4	POLDER & GLI/ADEOS
MODIS/EOS-Terra/1030	VIIRS/NPP
MODIS/ESO/Aqua	VIIRS/NPOES C1-1330
	OCEANSAT-2
	SGLI/GCOM-B1 and B2

APPENDIX I

ACRONYM LIST

ADCP – Acoustic Current Doppler Profiler
AMT – Atlantic Meridional Transect
ANIMATE – Atlantic Network of Interdisciplinary Moorings and Time Series for Europe
AOPC – Atmospheric Observations Panel for Climate
Argo – a global array of profiling floats
BATS – Bermuda Atlantic Time Series Station
BIO – Bedford Institute of Oceanography
BSH – Bundesamt für Seeschiffahrt und Hydrographie
CALCOFI – California Cooperative Oceanic Fisheries Investigations
CARIAOCA –
CARIOCA – Carbon Interface Ocean Atmosphere buoys
CAVASOO – Carbon Variability Studies by Ships of Opportunity
CDOM – Chromophoric Dissolved Organic Matter
CEOS – Committee on Earth Observation Satellites
CFC – Chlorofluorocarbons
CLIVAR – Climate Variability and Predictability Programme of WCRP
CRM- Certified Reference Material Programme
CTD – Conductivity, Temperature, Depth
DIC – Dissolved Inorganic Carbon
DOC – Dissolved Organic Carbon
DYFAMED – Dynamique des Flux Atmospheriques en Mediterranée programme
ECCO – Estimating the Circulation and Climate of the Ocean
EDOCC – Ecological Determinants of Ocean Carbon Cycling
ENSO – El Niño - Southern Oscillation
ESTOC - European Station for Time-Series in the Ocean Canary Islands
FAO – Food and Agriculture Organization
GAIM – Global Analysis, Integration, and Modelling
GCOS – Global Climate Observing System
GEOSECS – Geochemical Sections in the Ocean
GeP&CO – Géochimie, Phytoplancton et Couleur de l'Océan
GLI – Global Imager
GLOBEC – Global Ocean Ecosystem Dynamics
GODAE – Global Ocean Data Assimilation Experiment
GOOS – Global Ocean Observing System
GOSIC – Global Observing Systems Information Centre
GOSSP – Global Observing Systems Space Panel
GTOS – Global Terrestrial Observing System
HNLC – High Nitrate, Low Chlorophyll
HOT – Hawaiian Ocean Time-series
HPLC – High Performance Liquid Chromatography
ICSU – International Council for Science
IfM – Institut für Meereskunde
IGBP – International Geosphere – Biosphere Programme
IGFA – International Group of Funding Agencies for Global Change Research
IGOS – Integrated Global Observation Strategy
IOC – Intergovernmental Oceanographic Commission
IOCCG – International Ocean Colour Coordinating Group
JAMSTEC –Japanese Marine Science and Technology Centre
JGOFS – Joint Global Ocean Flux Study
KERFIX – Fixed Station at Kerguelen Island
KNOT - Kyodo North Pacific Ocean Time Series
LEO-15 – Long-term Ecosystem Observatory at a 15 Meter Depth (Rutgers University, USA)
LOICZ – Land-Ocean Interactions in the Coastal Zone
LTER – Long-Term Ecological Research Project
MBARI – Monterey Bay Aquarium Research Institute
MERCATOR – General circulation modeling project for operational oceanography (France)
MERIS – European Medium Resolution Imaging Spectrometer
MOBY – Marine Optical Buoy
MODIS – Moderate Resolution Imaging Spectrometer
NAO – North Atlantic Oscillation
NASA – National Aeronautics and Space Administration
NCAR – National Center for Atmospheric Research (USA)
OCI – Ocean Colour Imager
OCMIP – Ocean Carbon Model Intercomparison Project
OCTET – Ocean Carbon Transport, Exchanges and Transformations
OCTS – Ocean Colour and Thermal Scanner
OISO – L'océan Indien service d'observation
OOPC – Ocean Observations Panel for Climate
OSMI – Ocean Scanning Multispectral Imager
PAGES – Past Global Changes Programme
PALACE – Profiling Autonomous Lagrangian Circulation Explorer
PAR – Photosynthetically Active Radiation
PDO – Pacific Decadal Oscillation

PIRATA - Pilot Research Moored Array in the Tropical Atlantic
POLDER – Polarization and Directionality of the Earth's Reflectance
SAMI – Submersible Autonomous Moored Instrument for seawater CO_2
SAVE – South Atlantic Ventilation Experiment
SCOR – Scientific Committee on Oceanic Research
SEATS – South East Asia Time Series Station
SeaWiFS – Sea-viewing Wide Field of View Sensor
SIMBIOS – Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies
SOLAS – Surface Ocean-Lower Atmosphere Study
SOOP – Ship-of-Opportunity Programme
TAO – Tropical Atmosphere – Ocean Buoy Array
TOPC – Terrestrial Observations Panel for Climate
TTO – Transient Tracers in the Ocean
UNEP – United Nations Environment Programme
UNESCO – United Nations Educational, Scientific, and Cultural Organization
VOS – Volunteer Observing Ships
WCRP – World Climate Research Programme
WMO – World Meteorological Organization
WOCE – World Ocean Circulation Experiment

APPENDIX II

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