JOINT GLOBAL OCEAN FLUX STUDY

A Core Project of the International Geosphere-Biosphere Programme

JGOFS REPORT No. 33

JOINT IGBP EU-US MEETING ON THE OCEAN COMPONENT OF AN INTEGRATED CARBON CYCLE SCIENCE FRAMEWORK

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26 Report of the JGOFS/LOICZ Continental Margins Task Team Meeting, No 2. October 1997
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28 Eleventh meeting of the JGOFS SSC; Twelfth meeting of the JGOFS SSC; and the Second meeting of the North Pacific Task Team. November 1998
29 JGOFS Data Management and Synthesis Workshop, 25-27 September 1998, Bergen, Norway. Meeting Minutes. January 1999
30 Publications 1988-1999. January 2000
31 Thirteenth meeting of the JGOFS Scientific Steering Committee. Fourteenth meeting of the JGOFS Scientific Steering Committee. Fifteenth meeting of the JGOFS Scientific Steering Committee. October 2001
32 Meeting of the Southern Ocean Synthesis Group, Year 1998. October 2001.

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- North Atlantic Planning Workshop. Paris, 7-11 September 1987
- SCOR Committee for the Joint Global Ocean Flux Study. Report of the First Session. Miami, January 1988
- Report of the First Meeting of the JGOFS Pilot Study Cruise Coordinating Committee. Plymouth, UK, April 1988
- Report of the JGOFS Working Group on Data Management. Bedford Institute of Oceanography, September, 1988

JOINT GLOBAL OCEAN FLUX STUDY

– JGOFS –

REPORT No. 33

JOINT IGBP EU-US MEETING ON THE OCEAN COMPONENT OF AN INTEGRATED CARBON CYCLE SCIENCE FRAMEWORK

This report from the EU-USA Paris Workshop is being provided as *work-in-progress*. The purpose is to share with a broader community some of the detailed planning that is being considered within the ocean carbon cycle community, as a contribution to the larger goal of planning for the next decade of integrated carbon cycle research.

CONTENTS

JGOFS Report No 33

JOINT IGBP EU-US MEETING ON THE OCEAN COMPONENT OF AN INTEGRATED CARBON CYCLE SCIENCE FRAMEWORK

by

Ken Caldeira, Hugh Ducklow, Hein de Baar, Nicolas Gruber, Christopher L. Sabine and Doug W.R. Wallace

PREFACE

As we enter the 21st century, society's need for knowledge of the complexities and interactions of the Earth system in order to make informed decisions is tremendous. To meet this challenge, the International Geosphere-Biosphere Programme (IGBP), World Climate Research Programme (WCRP), and the International Human Dimensions Programme (IHDP) are planning the next stage of fully coupled, integrated global scale research. The Programmes have selected three themes around which to orient research activities in the coming decade: food systems, water resources and carbon cycle.

The atmospheric concentration of carbon dioxide, the second most abundant greenhouse gas after water vapour, has steadily risen over the past 150 years, leading to concerns about effects on the carbon cycle and the Earth System. Therefore, carbon cycle research has become a dominant theme in Earth System Science and predicting the course of carbon in the environment is a top priority for many national science programmes.

National and international planning for carbon cycle research has been underway for the past few years, in the form of workshops to evaluate the state of current knowledge, publications summarizing that knowledge, and development of research plans for the next decade. Science planning in the IGBP/WCRP/IHDP will culminate in the development of an Integrated Carbon Cycle Framework.

The Integrated Carbon Cycle Framework is addressing the oceanic, terrestrial, atmospheric and human dimensions of the carbon cycle. Two preparatory workshops were organized, one focusing on terrestrial aspects and one focusing on oceanic aspects of the global carbon cycle. The workshop on Terrestrial Carbon Research was held in Costa da Caparica, Portugal, 22-26 May 2000. The Oceanic Carbon workshop was held at UNESCO in Paris, France, 6-8 September 2000, graciously hosted by the IOC office, with funding for participant travel by the European Commission and the U.S. National Oceanic and Atmospheric Administration. Philippe Ciais, LSCE (CEA/CNRS) chaired the meeting and, along with Art Alexiou of the IOC, provided excellent local logistical support. The results of this workshop, which are summarized in this volume, were incorporated into a broader workshop, held in Durham, New Hampshire in October 2000, to develop the full Integrated Framework.

This volume is being provided as work-in-progress. The purpose is to share with a broader community some of the detailed planning that is being considered within the ocean carbon cycle community, as a contribution to the larger goal of planning for the next decade of integrated carbon cycle research.

We thank the JGOFS International Project Office for sponsoring the publication of this volume and shepherding its completion. Finally, we thank the participants of the meeting for their dedication to this effort, and look forward to the exciting promise of the next decade of carbon cycle science.

Claus Brüning

European Commission

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WORKING GROUP 1

OCEAN CARBON OBSERVATIONS

Prepared by
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INTRODUCTION

Public awareness of human impacts on the local, regional and global environment is very high. The public's interest in having access to accurate information concerning changes to their environment is also very high. One of the major foci of such interest and concern is the effect of human activity and climate on the oceans and the global carbon cycle. There is also an immediate socio-political requirement for better understanding of the global carbon cycle because of the 1997 endorsement of the Kyoto Protocol. CO_2 that is stored in the ocean does not affect the earth's radiation balance, so the oceanic uptake of anthropogenic CO_2 mitigates the potential for global warming. Attempts to limit the future atmospheric CO_2 growth, however modest, will involve major, and potentially costly, changes in energy and technology policy. Future assessments 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, including the ocean.

> *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.*

Government leaders and the public are looking to the scientific community to provide continuing assessments of the impact of anthropogenic CO_2 and climate change on the oceans as well as potential feed-backs to the atmosphere.

The most robust way to assess the global carbon cycle will ultimately require the combination of comprehensive carbon measurement programmes and the advancement of coupled carbon-cycle ocean-land-atmosphere prognostic/assimilative models. Until that time, the complexity and variability of carbon storage and uptake on land means 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 to constrain the global CO_2 budget for at least the near future. In addition, inverse modelling techniques are being developed which utilize constraints imposed by atmospheric, oceanic and terrestrial measurements. Both approaches rely on access to a set of relevant and high-quality observations covering regional and global scales.

A comprehensive observation programme is also necessary to address scientific issues directly related to the oceanic role as a sink for anthropogenic CO_2. One of the key questions that must be addressed is:

> **What is the regional to global scale distribution and seasonal to decadal scale variability of both natural and anthropogenic carbon sinks and sources in the ocean?**

Our understanding of the role of the oceans in the global carbon cycle and the oceanic uptake of anthropogenic CO_2 has been greatly advanced by recent international programmes such as the World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux Study (JGOFS), and the Land-Ocean Interactions in the Coastal Zone (LOICZ). Programmes such as these, together with much advancement in ocean carbon modelling, have improved our current understanding of ocean carbon inventories and transports, transfers across the atmosphere-ocean boundary, and transfers across the land-ocean boundary. A summary of some of these major advancements provides the background on which a future observational programme is proposed.

OCEAN CARBON INVENTORIES AND TRANSPORTS

Databased estimates of the current oceanic anthropogenic CO_2 inventories and transports have been greatly improved by the recent global survey efforts of WOCE and JGOFS. By working together, these programmes have produced a large number of high quality measurements of important anthropogenic tracers such as dissolved inorganic carbon (DIC), chlorofluorocarbons (CFCs), and radiocarbon (^{13}C and ^{14}C), as well as other chemical species important in the study of biogeochemical cycling. Data from these cruises are now becoming available and synthesis results are being published. Carbon data from the Indian Ocean, for example, were used recently by Sabine *et al.* (1999) to estimate the anthropogenic CO_2 inventory in that ocean basin. Sabine *et al.* (1999) total anthropogenic CO_2 inventory estimates, based on the C* method of Gruber *et al.* (1996), showed that the highest concentrations and the deepest penetrations of anthropogenic CO_2 are associated with the Subtropical Convergence with very little anthropogenic CO_2 in the high latitude Southern Ocean (south of 50ºS). Holfort *et al.* (1998) used data from three WOCE/JGOFS sections together with several pre-WOCE cruises in the South Atlantic between 10 and 30ºS to estimate meridional carbon transports in this region. Notable findings by Holfort *et al.* are that the net pre-industrial carbon transport across 20ºS was toward the south, but the net anthropogenic CO_2 transport is toward the north. This results from the fact that the anthropogenic carbon is generally restricted to the upper, northward moving waters and the southward moving North Atlantic Deep Waters have not yet been contaminated by the anthropogenic signal at this latitude.

Another major success of the past decade of ocean carbon cycle research has been the development and testing of a wide variety of models suited to assessing current ocean carbon inventories and future uptake of anthropogenic CO_2. Since the first global ocean circulation simulation by Bryan (1969), a variety of models have been formulated with widely different configurations, for example, with respect to their grid systems, surface boundary conditions, and eddy mixing schemes, all of which affect the model circulation. Global CO_2 uptake estimates from some ocean biogeochemical models have been compared (Orr, 1993; Schimel *et al.*, 1995, Siegenthaler and Sarmiento, 1993); However detailed comparisons were not feasible because of the different protocols employed for both modelling and analysis by the different groups. Recently the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP; *http://www.ipsl.jussieu.fr/ocmip/*) with wide participation from the US and European communities, Japan, and Australia, brought together more than a dozen 3-D models to compare a standard set of simulations. The standardized OCMIP simulation protocols made it possible to highlight those model differences due to ocean circulation rather than those due to the gas exchange or to the representation of ocean biogeochemistry (*e.g.*, Orr *et al.*, 2001).

The results of OCMIP show significant differences in the distributions of simulated tracers by the different models and between the models and the WOCE/JGOFS observations (*e.g.*, **Figure 1**). The global magnitude of the present day oceanic anthropogenic CO_2 sink, however, is relatively similar between the different models. These estimates also agree with an independent estimate of the anthropogenic CO_2 uptake rate based on O_2 /N_2 time-series in the atmosphere (Battle, 2000). The models, however, show much less agreement with respect to where this anthropogenic CO_2 is being stored in the ocean (*e.g.*, **Figure 2**).

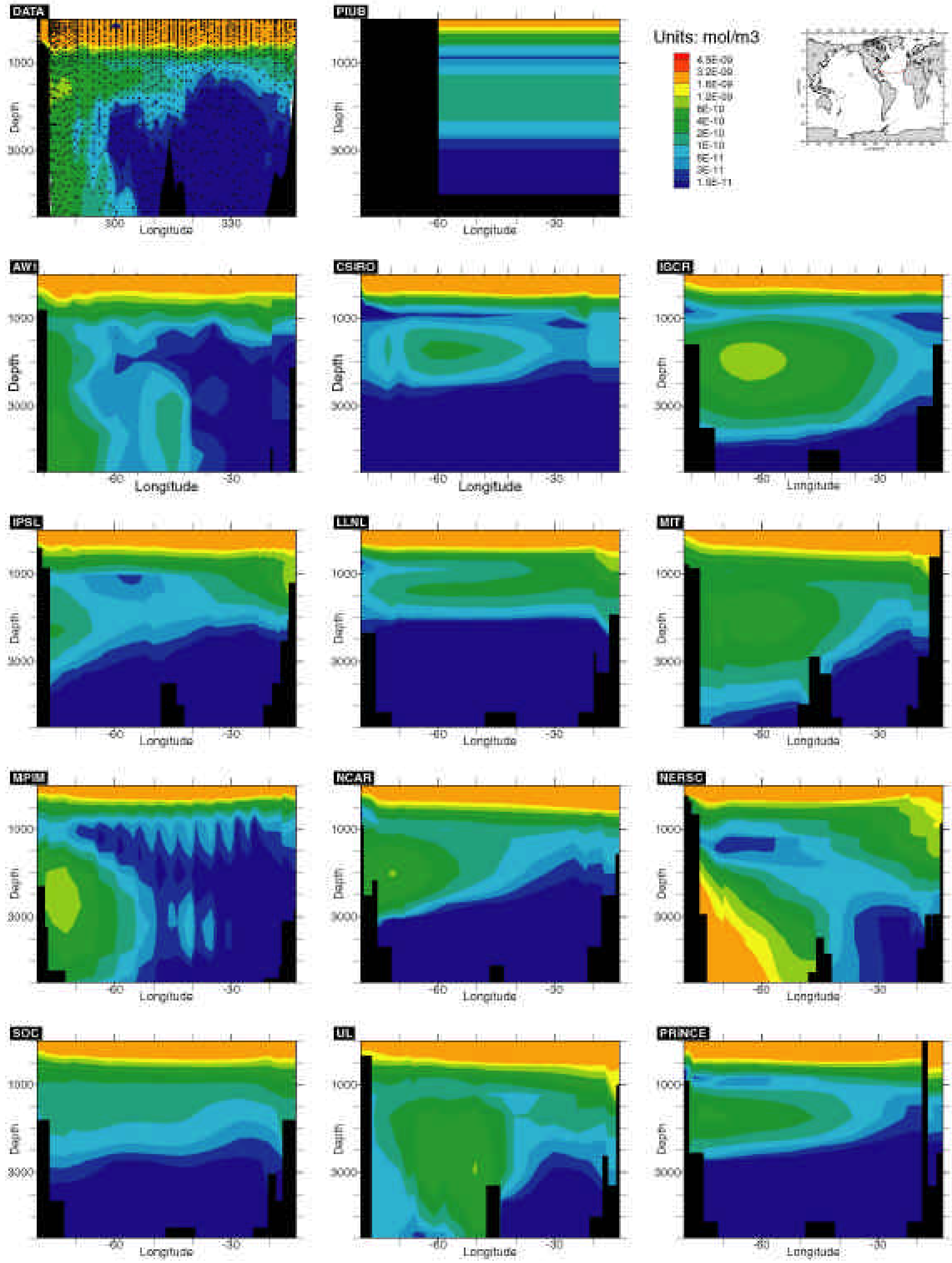

Figure 1. East-west sections of CFC11 (mol m^{-3}) in the North Atlantic at 24°N from observations ("DATA") and from simulations by OCMIP models Dutay *et al.*, 2001. Participating models in OCMIP: AWI =Alfred Wegener Institute for Polar and Marine Research, Germany; CSIRO =CSIRO Division of Marine Research, Australia; IGCR/CCSR =Institute for Global Change Research, Frontier Research, Japan; IPSL =Institute Pierre Simon Laplace, France; LLNL =Lawrence Livermore National Laboratory; MIT =Massachusetts Institute of Technology; MPIM =Max Planck Institut für Meteorologie - Hamburg, Germany; NCAR =National Center for Atmospheric Research; NERSC =Nansen Environmental and Remote Sensing Centre, Norway; PIUB =Physics Institute, University of Bern, Switzerland; PRINCE =Princeton University/ Geophysical Fluid Dynamics Laboratory; SOC =Southampton Oceanography Centre, UK; UL =University of Liège/Université Catholique de Louvain, Belgium.

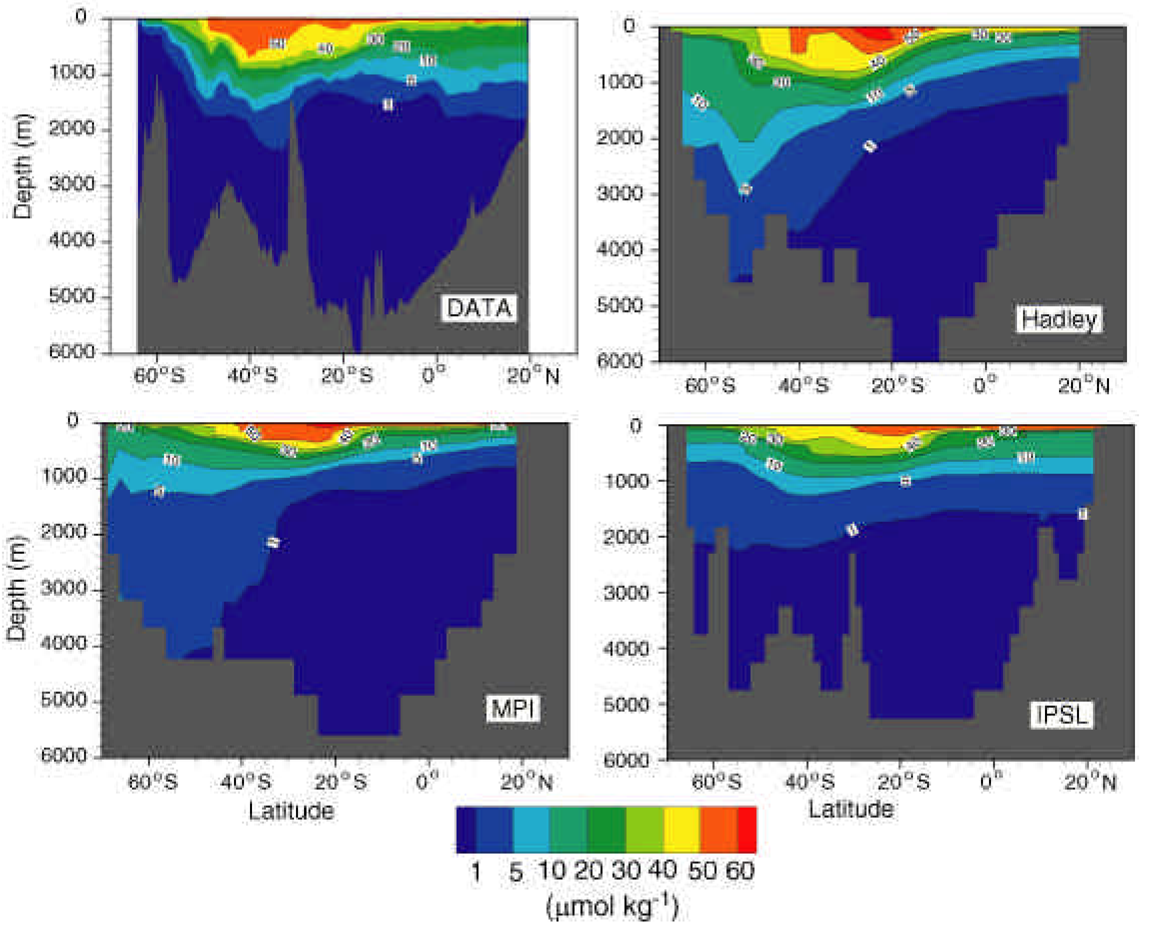

Figure 2. North-south section of anthropogenic CO_2 (μmol kg-1) in the Indian Ocean at 92ºE from observations ("DATA") and from simulations by OCMIP models. Model abbreviations are: MPI = Max Planck Institut für Meteorologie - Hamburg, Germany; Hadley =Hadley Centre for Climate Prediction and Research, Bracknell, England, UK; IPSL =Institute Pierre Simon Laplace, France

The differences amongst the models and between the models and observations may arise from two separate sources. The first is that the databased anthropogenic CO_2 values are derived quantities, while in the models they can be unambiguously defined. Insofar as the assumptions that were involved in estimating these quantities from observations are incorrect, the derived quantities will exhibit biases relative to the models. A second source of discrepancies is differences in the model circulation. Different models have different pathways and rates of vertical exchange. The uptake of different tracers will be strongly affected by the interplay between vertical exchange and gas exchange. Since gas exchange is standardized in all the OCMIP models (though it may still differ substantially from the true gas exchange), differences amongst the models arise from differences in the vertical exchange. Differing types of vertical exchange further complicate this picture. For example, a parcel that is upwelled in the Southern Ocean and downwelled soon after as Weddell Sea Bottom Water may pick up substantial amounts of CFC, less CO_2 and even less ^{14}C. The shorter the residence times at the surface ocean, the greater the difference between the tracers because of different gas exchange rates. By contrast, a case where a parcel is mixed up to the surface by convection, re-injected into the interior, then mixed up again, will tend to reduce the importance of gas exchange, since the parcel can come into contact with the atmosphere many times before finally leaving the region. Different model parameterizations may result in different types of vertical exchange, a process that is very difficult to sort out with only a few shipboard observations.

This example highlights the value of a comprehensive observational programme to study ocean ventilation and circulation as well as the biogeochemistry. It also shows the utility of having contrasting tracers and the need for caution when attempting to use observations of other tracers to infer anthropogenic CO_2. Future measurement-based inventory estimates of anthropogenic CO_2 and other tracers will provide a powerful constraint for the model parameterizations and will lead to improved techniques for the data-based estimates.

TRANSFERS ACROSS THE ATMOSPHERE-OCEAN BOUNDARY

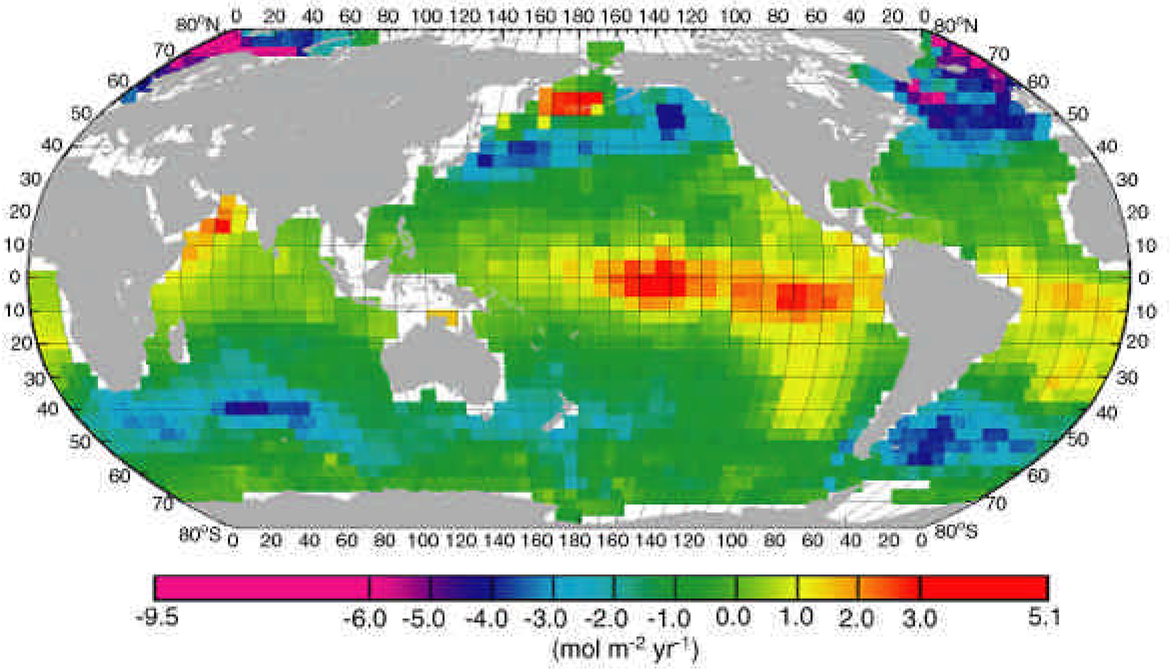

Figure 3. Map of air-sea CO_2 flux (mol m^{-2} yr^{-1}) from Takahashi *et al.*, 1999.

Global and to some extent the regional patterns of CO_2 uptake by the ocean on decadal timescales are reasonably well constrained by a variety of techniques including: numerical models (often calibrated/validated with ^{14}C and other transient tracers), surface ocean pCO_2 measurements, oceanic isotopic ^{13}C inventories, temporal evolution of dissolved inorganic carbon (DIC) fields, and empirical data-based anthropogenic CO_2 estimates. The first comprehensive global estimate of CO_2 flux based on ? pCO_2 measurements was presented by Tans *et al.* (1990). The ? pCO_2 based flux estimates, together with an atmospheric transport model, suggested that the oceanic uptake was substantially less than the indirect methods suggested. The Tans *et al.* estimate was revised from 0.3-0.8 to 0.6-1.34 PgC yr^{-1} with the addition of more data and a lateral advection-diffusion transport equation to perform the necessary temporal and spatial interpolations (Takahashi *et al.*, 1997). The increased uptake estimate of 2.17 PgC yr^{-1} (Takahashi *et al.*, 1999) resulted from the addition of critical data from the Indian Ocean and a change in the virtual year the data were normalized to from 1990 to 1995 (atmospheric CO_2 increased by ~ 7 ppm in that 5 year period). **Figure 3** shows a map of the air-sea fluxes based on this latest compilation.

The significant changes in the uptake estimates reflect the sensitivity of this estimate to the data coverage and the interpolation scheme necessary to produce the global estimates. The latest ? pCO_2 based flux estimate includes pCO_2 measurements collected over 40 years. Despite pulling together all these data, there are large ocean regions that have little or no coverage during certain months. This is important because natural seasonal and interannual variations in local air-sea fluxes can be one to two orders of magnitude larger than the net annual flux.

Information on global decadal and interannual variability of the oceanic and terrestrial sinks comes primarily from atmospheric CO_2, O_2/ N_2, and oceanic ^{13}C trends. Different approaches, however, have resulted in very different estimates of variability of the oceans. Some direct estimates of regional interannual variability in air-sea flux are emerging from repeat observations of surface water pCO_2. **Figure 4** illustrates the interannual variability in sea surface pCO_2 and air-sea flux associated with changes in El Niño Southern Oscillation (ENSO) conditions in the Equatorial Pacific. During non-El Niño conditions, the eastern Equatorial Pacific (10ºS-10ºN and 80ºW- 135ºE) is estimated to be a 0.6-0.9 PgC yr^{-1} source of CO_2 to the atmosphere, but this can be reduced by nearly half during strong El Niño periods (Feely *et al.*, 1999).

The time distribution of the data used to generate the Takahashi *et al.* (1999) map is heavily weighted towards the latter years. It may be conceivable to generate a flux climatology based only on data collected in the 1990s. In the future, we should strive towards reducing the timeframe necessary to generate climatology maps to the point where a databased global flux map can be generated from a single sampling year. Spatio-temporal coverage at this level will provide a much better understanding of the CO_2 flux distributions and variability. This information, in turn, can be used to evaluate carbon models and through inversion techniques currently being developed determine the uptake rates for both the ocean and the terrestrial biosphere.

TRANSFERS ACROSS THE LAND-OCEAN BOUNDARY

The coastal zone is a region of the ocean that interacts strongly and complexly with the land, adjacent atmosphere, and open-ocean. It is a region of important commercial fisheries, a spawning ground for many marine organisms, a haven for coral reefs, and a major site of tourism activities. With an area about one-tenth of that of the open ocean, at least 10% of oceanic primary production occurs in coastal waters, representing significantly higher specific rates of organic productivity in this region than in the open ocean. In addition, 8 to 30 times more organic carbon and 4 to 15 times more calcium carbonate per unit area accumulate in the coastal ocean than in the open ocean. In addition, coastal gas exchange fluxes of carbon, nitrogen, and sulfur in coastal waters are considerably higher than in the open ocean. Nearly 60% of the world's current human population lives within 100 kilometres of the coast, and the numbers of people are increasing every year as people move from continental interiors to urbanized centres on the coast or to immediately adjacent riverine watersheds.

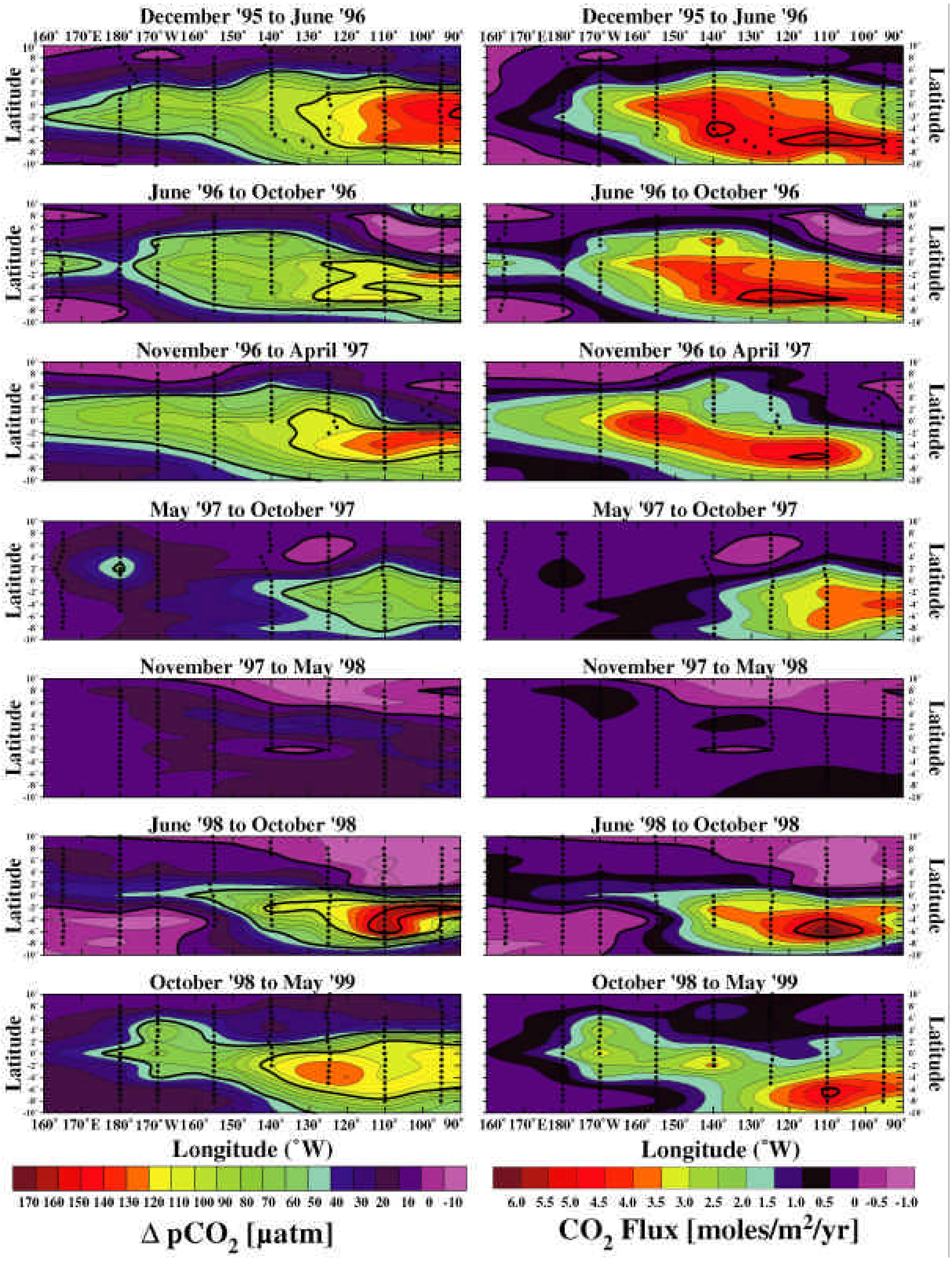

Figure 4. Maps of ? pCO_2 and air-sea flux in the equatorial Pacific for different time periods from Feely *et al.*, 2001a.

Much needs to be learned about the coastal zone carbon cycle and the role of this region in air-sea exchange of CO_2. This is due in part to the lack of a concerted effort to collect, on a global scale, observational data dealing with air-sea CO_2 exchange in this region. Several investigators have tried to use limited data to evaluate the role of the coastal zone in the global carbon cycle (*e.g.*, Mackenzie *et al.*, 2000; Ver *et al.*, 1999; Gattuso *et al.*, 1999; Mackenzie *et al.*, 1998; Smith and Mackenzie, 1987). In a nutshell because of the accumulation of $CaCO_3$ in coastal zone sediments and because of 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. Today is a problem, as CO_2 has built up in the atmosphere, the tendency for CO_2 to invade coastal zone waters has become important. Some modelling 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 evasion flux and CO_2 will invade coastal waters on a global scale. These conclusions are open to debate and controversy in part because there has not been a good global observational programme for coastal waters.

The Land-Ocean Interactions in the Coastal Zone (LOICZ; *http://kellia.nioz.nl/loicz/*), one of the seven Core Projects of the IGBP, focuses on the coastal zone, where the land, ocean, and atmosphere meet and interact. The overall goal of the project is to determine at regional and global scales, the nature of the dynamic interaction; how changes in various compartments of the Earth system are affecting coastal zones and altering their role in global cycles, particularly of C, N, and P; to assess how future changes in these areas will affect their use by people; and to provide a sound scientific basis for future integrated management of coastal areas on a sustainable basis. As part of this project, a number of coastal areas have been investigated in terms of their C, N, and P balances. Carbon budgets for the world’s coastal seas are anticipated for up to 100 areas. However, this project, or any other, has not established any sort of observational system in terms of determining the role of the global coastal zone as a net source or sink of atmospheric CO_2. This is partly because the global coastal zone is a very heterogeneous oceanographic region.

STRATEGY FOR AN INTERNATIONAL OBSERVATIONAL PROGRAMME

While the programmes discussed above along with other advances not discussed represent significant accomplishments, there are still many specific issues that need to be addressed including:

- What is the best method for reducing the large uncertainty in the current estimates of the distribution and variability of air-sea fluxes in the ocean?
- What is the best method for reducing the uncertainty in the current estimates of natural and anthropogenic CO_2 storage and transport within the ocean?
- What is the role of the Southern Ocean in the uptake and storage of anthropogenic carbon?
- What is the role of the Equatorial Pacific in determining interannual variability of oceanic sink?
- What is the role of coastal margins in the global carbon cycle?
- How will these change in the future?
- What observations are necessary in time and space to constrain future estimates of the sources and sinks, assess the effectiveness of carbon management and sequestration activities, and to monitor for future risks and surprises in the response of the oceanic system to global climate change?

The potential currently exists to greatly improve our understanding of ocean carbon-cycle behaviour through the coordinated use of recent advances in measurement technologies and modelling techniques. There are several U.S. and international groups discussing the development of various aspects of a global ocean carbon-monitoring programme. For example, within the U.S., a NOAA CO_2 observational planning group is preparing a document to be released this Fall, 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. The SCOR-IOC CO_2 advisory panel has also discussed and proposed certain elements for a monitoring system. A summary of organizations working towards an ocean observing system with contact information can be found in **Table 1**. It is imperative that close coordination at the international level takes place to help these programmes work toward complimentary goals and minimize a duplication of efforts.

Table 1: organizations that have discussed global carbon monitoring programmes

Programme	Realm	Web Site
SOLAS	Boundary layer exchanges	*www.ifm.uni-kiel.de/ch/solas/main.html*
IGOS-P	Global Carbon Cycling	*www.unep.ch/earthw/igos.htm*
US SOLAS	Boundary layer exchanges	*www.aoml.noaa.gov/ocd/solas/*
OCTET	Ocean Carbon Cycling	*Alpha1.msrc.sunysb.edu/octet/*
EDOCC	Ecosystem functional groups	*picasso.oce.orst.edu/ORSOO/EDOCC/*
GOOS	Global Ocean Observations (physical)	*ioc.unesco.org/goos/*
CLIVAR	Ocean Climate Variability	*www.clivar.org/*
SCOR-IOC CO_2 Panel	Ocean Carbon Cycling	*ioc.unesco.org/ioc19/ioc19item617.htm*

What follows is a description of the key efforts suggested for an ocean carbon cycle observational network that addresses the three major research areas mentioned in the previous sections. The objectives and description are heavily based on planning documents of affiliated efforts.

Oceanic Inventories and Transport

To understand the role of the oceans in the global carbon cycle, one must first determine the distribution and transport of carbon in the oceans. The WOCE/JGOFS survey during the 1990s has provided a full depth global data set of unprecedented coverage and quality. A repeat measurement programme can leverage these baseline results to evaluate future changes in ocean carbon inventories and circulation. Repeat measurements of ocean carbon concentrations provide the most direct assessment of changes in ocean carbon inventory and the oceanic storage of anthropogenic CO_2. These measurements also allow us to evaluate changes in ocean circulation and carbon storage using time scales (rates) from transient tracer measurements. Finally, repeat ocean measurements provide a strong constraint for evaluating ocean carbon models.

Preliminary efforts to compute the regional and basin-scale horizontal carbon transport within the ocean using hydrographic sections and inverse techniques has been very promising. Ocean carbon transport has two intrinsic science issues of high relevance to a CO_2 ocean observation plan: (1) The "natural" transport of oceanic carbon is a key constraint for modelling and interpreting the meridional atmospheric gradients and (2) by studying the transports from "boxes" bound by high quality observations the divergences in natural and anthropogenic CO_2 can pinpoint the long term sources and sinks of CO_2 that can be compared with models and observations of air-sea CO_2 flux.

The objectives are: (1) to quantify changes in the rates and spatial patterns of oceanic carbon uptake, fluxes and storage of anthropogenic CO_2, (2) to detect and quantify changes in water mass renewal and mixing rates, and (3) to provide a validation of modelled natural and anthropogenic climate variability. The strategy is to put in place a global ocean-observing network for CO_2 and tracers to document the continuing large-scale evolution of these fields. It is proposed that a set of the hydrographic sections, many of them repeats of WOCE Hydrographic Programme sections, be occupied at time intervals of between 5 and 10 years to provide broad-scale global coverage of ocean variability. The sampling time interval should provide resolution of the local ventilation time-scales below the main thermocline to determine interannual and decadal scale changes in oceanic fluxes (Taft *et al.*, 1995). However, attention must be paid to potential biases resulting from seasonal variability in the transport and an intense period of seasonal sampling may be required to evaluate this issue.

Station spacing on the proposed sections should be 30-60 nautical miles to avoid aliasing by eddies and other mesoscale variability into the inferred climate signal. An initial suggestion is that 30 mile spacing is necessary on zonal lines, but somewhat coarser resolution (60 miles) may be acceptable on meridional lines (except at the equator, in frontal regions, or near coastal boundaries). The number of lines required to constrain the major oceans is estimated to be at least 2-3 meridional and 2-3 zonal sections per ocean (Taft *et al.*, 1995; Feely *et al.*, 2001b). Meridional sections are important for understanding variations in basin-scale circulation patterns and inventory changes. Repeat occupation of zonal sections allows for the detection of variability in the rates, pathways, and properties of deep and intermediate waters carried towards the equator from the high latitudes and zonal variations in carbon storage. Zonal sections are also required for mass and carbon transport calculations. Ideally, they should be coast-to-coast sections located downstream of the deep and intermediate water formation regions.

The inorganic carbon measurement suite should include DIC, total alkalinity and frequently a third/fourth CO_2-system property such as pH and/or pCO_2 to assure proper characterization of the inorganic carbon speciation. To understand the processes controlling the uptake of CO_2 from the atmosphere additional variables to be measured should include: total or dissolved organic matter, temperature, salinity, nutrients, oxygen, and related tracers (CFC's and HFC's, ^{14}C, ^{13}C, ^{3}H / ^{3}He, *etc.*). The additional tracers provide important information on the processes acting on the carbon system. The transient tracers play a key role because they provide temporal information about ocean mixing and advection that is essential to interpreting fossil CO_2 distributions (*e.g.*, water mass ages, transport fluxes) and provide a complementary approach to monitoring DIC inventory changes. Some of these tracers provide time histories over a range of scales from days to centuries.

To first order, the long-term oceanic uptake of anthropogenic CO_2 is regulated by water mass transport. Continued improvements in observations and modelling of ocean ventilation (mean and variability), therefore, are essential components of a carbon-observing plan. Connections with hydrographic and climate programmes such as CLIVAR are critical in this regard. The repeat hydrographic survey lines proposed for CLIVAR, for example, are consistent with the requirements for the carbon measurement programme outlined here [Gould and Toole, 1999; Rintoul *et al.*, 1999] (**Figure 5**). The potential benefits of such cruises, including the provision of calibration data for autonomous sensors, in particular salinity data for the ARGO project, improved knowledge of the rate of change of heat and freshwater storage and fluxes, and an assessment of changes in deep and shallow water-mass formation and overturning are some of the primary goals of CLIVAR.

The repeat sections should be integrated with the high-frequency water column sampling networks like the time-series and mooring sites to quantify seasonal and interannual variability between cruises that could bias results. These sites can also be used to monitor for unexpected changes that could require reoccupation of lines earlier than expected. For example, a shut down in the thermohaline circulation of the North Atlantic by capping the subpolar region with a layer of warm fresh water has been postulated as a consequence of changes in precipitation patterns related to a warmer climate. Both modelling and paleo-oceanographic studies suggest that the ocean’s response to climate forcing can be rapid. It is imperative that we put ourselves in a position to detect such changes early and respond with additional surveys and process studies as necessary. The manned time-series sites also provide ideal test-beds for validation of autonomous sensors (*e.g.*, moored profiling carbon sensors) that eventually can be used to expand the time-series network and provide high-resolution measurements in remote areas. Towed undulating systems can also be used to examine higher frequency variability in the upper few hundred meters because of their reduced ship-time requirements relative to conventional survey cruises.

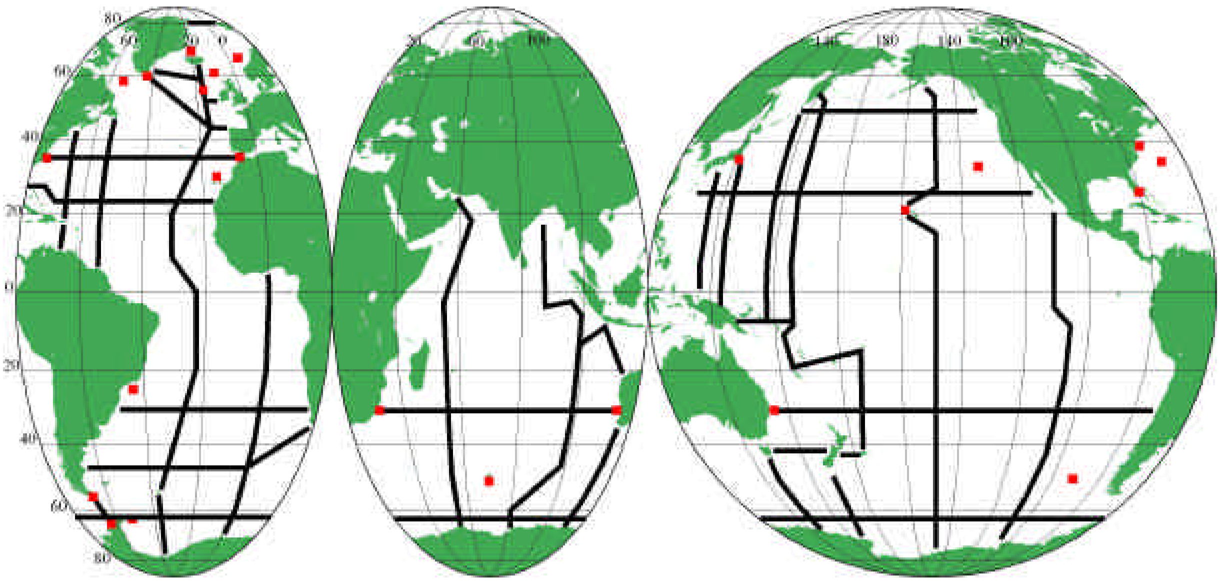

Figure 5. Potential sections and time-series stations suggested for CLIVAR (based on a composite of information in Gould and Toole [1999] and Rintoul *et al.* [1999].

Finally, it is important to emphasize the continued development of autonomous sensors for making water column measurements. At least two carbon parameters need to be measured by the water column sensors to constrain the carbon system. Tremendous advancements have been made in recent years on autonomous pH and pCO_2 sensors. Unfortunately, this is not an ideal pair for carbon system calculations. Advances in the autonomous detection of DIC or total alkalinity would be extremely useful for the water column measurements. Fixed subsurface and profiling carbon systems on moorings are already in the development stages and should be continued. Expansion of this technology to profiling floats and gliders could augment the repeat survey work in the future to help reduce the substantial personnel and monetary requirements of conventional survey cruises.

Air-Sea Fluxes

There are several independent measurement-based approaches available for estimating the current global uptake rate of anthropogenic CO_2 by the oceans including: inversions of atmospheric CO_2, atmospheric O_2/N_2, d^{13}C, and ? pCO_2 measurements. A comprehensive observational programme 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. The relative merits, problems, and appropriate sampling strategy for the atmospheric programmes are discussed elsewhere. We do note, however, that there should be strong links between the atmospheric and oceanic observational programmes. The atmospheric sampling network should take advantage of the many ocean platforms to augment the atmospheric sampling network. Likewise, ocean flux estimates are strongly dependent on high quality values generated from the global atmospheric CO_2 observational network.

Atmospheric measurements can provide global and/or hemispheric estimates of the seasonal and interannual variability in ocean uptake, but fast 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. There is basic agreement about the programme elements required for an oceanic observational programme to constrain air-sea CO_2

fluxes. Large-scale spatial coverage on Volunteer Observing Ships (VOS) and drifters, high-resolution temporal measurements at time-series stations and moorings, and technology improvement particularly in gas exchange parameterizations, data assimilation and use of remote sensing products.

The sea surface pCO_2 values required to estimate the air-sea carbon flux, is one of the few chemical parameters routinely measured with high spatial resolution. Shipboard underway pCO_2 systems are commonly used on oceanographic research cruises (a recent example being the WOCE/JGOFS hydrographic survey) as well as an expanding commercial ship effort. For example, a joint Japanese and Canadian pCO_2 VOS line (M/S Skaugran; *http://www.mirc.jha.or.jp/minnano/CGER_NIES/skaugran/index.html*) was maintained from 1995 to 1999 in the North Pacific. Coverage of the pCO_2 field in the Equatorial Pacific, a region of known large variability in air-sea CO_2 exchange due to ENSO, has been monitored since 1992 by NOAA investigators using underway systems on the TOGA/TAO array service ships. There are several Antarctic re-supply ships that are being used to provide regular data, including the French OISO programme in the South Indian Ocean between Kerguelen Island and Amsterdam, and the UK Atlantic Meridian Transect. Canada also operates a time-series line, 'line P', in the North Pacific. These vessels make transects generally twice a year. Other VOS lines are planned for the near future, including a EU proposal for transects between Denmark and West Greenland, Hamburg and Halifax, and UK and Jamaica. In the US, NOAA is investigating suitable additional routes, possibly to include transects between Miami and the Straits of Gibraltar, and on high-density XBT lines in the Atlantic and Pacific. The SCOR/IOC CO_2 panel has as long standing goal to assimilate this data into a comprehensive dataset.

Surface pCO_2 drifter technology is advancing rapidly. Systems like the CARIOCA buoy (*http://www.lodyc.jussieu.fr/carioca/home.html*) have been deployed for as long as a year in a variety of oceanographic environments [Hood *et al.*, 1999; Boutin *et al.*, 1999a; Bates *et al.*, 2000; Bakker *et al.*, 2000; Hood *et al.*, 2000]. These systems can be used to "fill in" temporal information in isolated regions that are not amenable to VOS work. The Lagrangian nature of these systems can also be used to investigate the mechanisms controlling the temporal evolution of the surface pCO_2 fields.

Table 2: Time-series stations in the oceans.

Station Name; Location/Supporting Country	**CO_2**	**Autonomous Sensors**
Hydrostation S/BATS; Bermuda/US	Yes	Yes
Station Papa; NE Pacific, Canada	Yes	No
Mike; Norwegian Sea, Norway	No	No
HOT; Hawaii, US	Yes	No
KNOT; NW Pacific, Japan	Yes	No
ESTOC; Canary Islands, Spain/Germany	Yes	No
Bravo; Labrador Sea, Canada	No	No
Pacific 0º, 155ºW; 2S, 170ºW; US	Yes	Yes

The VOS and drifter network should be integrated with time-series stations and moorings to properly constrain the spatial and temporal variations in the pCO_2 fields. The number of time-series stations has grown substantially over the last few years (see **Table 2**). While most of these stations have some sort of carbon measurement programme, only a few make regular surface pCO_2 measurements and fewer still use autonomous sensors to get high-resolution pCO_2 records. All time-series locations should make surface pCO_2 measurements. The wide variety of data collected at the time-series sites can be used to investigate the mechanisms controlling the pCO_2 of the surface waters. Understanding these mechanisms is essential for regional and global scale extrapolations. The time-series sites also provide ideal test-beds for moored autonomous sensors. Frequent visits to the time-series site provide essential ground-truthing and makes servicing of the moored systems easier. In turn, a moored autonomous sensor at the time-series site can provide higher resolution temporal information to help interpret changes observed between time-series cruises.

New time-series stations need to be added in key regions (*e.g.*, deep and intermediate water formation regions) to monitor changes in a wider variety of environments. As the technology for moored autonomous systems improves, they can be used to augment the time-series network in remote locations. Another important tool to assist in getting global pCO_2 coverage is the wide variety of satellite products that are becoming available. A number of satellite data sets have direct applicability to the ocean carbon system. The most obvious are ocean colour data, which began with CZCS (1979-1986) and greatly expanded in recent years (OCTS 1996-1997; POLDER; SeaWiFS Fall 1997 to present). Other relevant physical data sets include sea surface altimetry (TOPEX/Poseidon, ERS) for mesoscale variability and physical circulation, sea surface temperature (*e.g.*, Pathfinder AVHRR and TRM, the latter being able to "see" through clouds), and surface wind speed (NSCAT, QuickScat). It is well known that satellites enable excellent spatio-temporal coverage and consistency of methodology, but they are limited by what they can measure and their resolution, and depth of penetration. Conversely, the sampling coverage that is only possible from satellite-borne sensors provides a powerful capability for integrating and constraining other observations and model results. Correlations between the various satellite products and the VOS and time-series networks should be examined to evaluate the potential of quantitatively estimating pCO_2 using satellite-based algorithms (*e.g.*, Boutin and Etcheto, 1997; Boutin *et al.*, 1999b). Although there is not the same pressing need to lobby for continuation of satellite-borne ocean observing systems as for *in situ* observations, it would be a mistake to take the present capabilities for granted. It is important we acknowledge and highlight advances in the development of algorithms to improve estimation of biogeochemical variables, and that we encourage and request the development of new sensor suites.

As a complement to the high-resolution pCO_2 measurement programme, large-scale surveys of surface ocean ^{13}C can provide an independent estimate of the oceanic CO_2 uptake [Tans *et al.*, 1993]. The use of ^{13}C measurements to estimate oceanic uptake has the advantage that the anthropogenic signal is relatively large compared to the seasonal or interannual signal. Relatively long gas-exchange equilibration times (~10 years) for ^{13}C, however, may make it difficult to identify seasonal or interannual changes in ocean uptake. Although the relationship between ^{13}C and ^{12}C changes remains uncertain, ocean ^{13}C changes provide an independent, complementary estimate of ocean CO_2 uptake. Reconstructions of ocean ^{13}C changes, in conjunction with reconstructed DIC changes, can also provide a constraint on carbon fluxes through the terrestrial biosphere [Keir *et al.*, 1998].

Progress at the international level in organizing and coordinating an air-sea flux observation system can been made by: (1) identifying and supporting those programme elements that are currently in operation (*e.g.*, time series stations and 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, and (3) developing a cooperative synergy with other physical, chemical and biological ocean field efforts with especial emphasis on CLIVAR and GOOS.

Finally, it must be recognized that surface CO_2 surveys do not yield by itself an air-sea CO_2 flux. The gas transfer velocity, k must be known as well (Note, k = F s ? pCO_2, where F is the air-sea CO_2 flux, s is the solubility which is a function of temperature and solubility, and ? pCO_2 is the partial pressure difference of CO_2 between the surface ocean and the atmosphere above). To obtain regional fluxes we must be able to relate the gas transfer velocity to environmental forcing and obtain global estimates of k on daily timescales, possibly by remote sensing (*e.g.*, altimeter backscatter, Frew *et al.*, 2000). The way to reach this goal involves developing new techniques to measure the gas transfer velocity, improved understanding of the controls of k, assessment of possible artifacts and biases and validation/verification of the results by independent approaches (*e.g.*, Watson *et al.*, 1991; Wanninkhof and McGillis, 1999). These new techniques will most likely be developed through focused process studies, but these studies should be closely coordinated with the large-scale programmes. The VOS and time-series networks can be used to evaluate newly developed algorithms with respect to other independent approaches for estimating ocean uptake (*e.g.*, atmospheric CO_2 inversions, O_2 / N_2, *etc*.).

Studies of the Coastal Zone

While air-sea fluxes control the exchange of CO_2 between the oceans and the atmosphere, there are a number of pathways for interaction between the land and oceans, including transport of organic and inorganic carbon *via* rivers and groundwater, riverine sources of nutrients which affects biological carbon cycling in the coastal zone, and exchanges with sediments along the continental margins. The land-sea interface is a very dynamic and poorly understood region. Multidisciplinary programmes, such as LOICZ, are starting to make progress towards understanding carbon and nutrient cycling in specific ecosystems. However, these programmes need to be put into a global context. An expansion of the LOICZ programme to focus more on continental shelf and slope processes is necessary to constrain the systems all the way from the estuary to the open ocean. These intensive, multidisciplinary study sites should be linked together with a programme of repeat surveys and time-series stations as outlined above for open ocean studies. Along coast, survey cruises can help constrain the spatial variability of different shelf regions. The volunteer observing ships that will be instrumented for open-ocean underway measurements regularly cross the continental shelf as they approach their port. These time-series transects can be used to evaluate the temporal variability of these regions. Coastal time-series stations can also provide temporal information. The coastal zone can make an ideal location for testing new mooring technology. Coastal moorings are easy to access and maintain, and the biogeochemical signals are generally very large relative to the open ocean so instrument precision is not as important. Satellite products can also be very helpful at constraining both the spatial and temporal variability of the coastal zone. Although the continental shelves only encompass a small percentage of the global ocean, it is important not to forget these regions and the potential significance of land-ocean interactions.

RELEVANT CHALLENGES AND PRIORITIES

The development of a programme on ocean carbon observation has a number of continuity, knowledge and technology challenges. Some of the most important challenges of the initial system development include: developing a coordinated global VOS network; establishing a consistent network of repeat sections to cover necessary regions; establishing new time-series stations in remote locations; developing automated sensor platforms to sample at required spatial/temporal frequency; developing a data management system capable of handling the volumes of data that will be generated with this programme; and developing a data assimilation approach for basin to global scale data compilations and assimilation into models. In addition, there are a number of specific scientific challenges for each of the approaches discussed here (*e.g.*, improved approaches for estimating anthropogenic CO_2 from water column measurements, developing schemes for interpolating a reduced repeat section programme to get global inventories, improved gas exchanges coefficient formulations, improved pCO_2 interpolation techniques). These challenges can affect the implementation and usefulness of the proposed observational programme and in some cases, may dominate the uncertainties in the global estimates. However, these issues are not easily addressed in a large-scale observational programme and are discussed in detail in other chapters.

There are many issues of cost, timing, and technical readiness that factor into implementing this plan. At this stage, it is not possible to provide a clear prioritised list of which observations are most important. Most oceanographers agree that a mix of repeat sections, time-series and VOS work needs to be implemented together with some emphasis on technology development. The exact details of this mix will have to be worked out as implementation of this plan draws closer.

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WORKING GROUP 2

OCEAN CARBON CYCLE PROCESS STUDIES

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INTRODUCTION

There are currently several very active nationally-based planning initiatives aiming at design, support and implementation of a new series of ocean carbon-related research programmes, and a number of workshops and symposia have been held to explore the rationale, new scientific questions and new tools for answering them. A further series of workshops is now being held in the international sphere to coordinate national programmes, and create an integrated attack on the global carbon cycle at the earth systems level. This document was drafted following a small meeting held in Paris, 6-8 September 2000 to pursue the oceans component of this larger research plan. The document benefited from discussions held at the Paris meeting, subsequent email exchange and contributions, and importantly, from other existing documents. Portions of the document below have been borrowed freely from some of the other reports. Among the principal documentary sources are:

Capone, D., C. Lee, and R. Wanninkhof, 2000. An Integrated Ocean Carbon Dynamics Plan for the Ocean Science. Synthesis Statement. (Working Draft, 21 Sep 2000; for presentation to US NSF).

Lee, C., 2000. ORACLE WORKING DRAFT (9/19/00). (Ocean Response to Anthropogenic Carbon L E). discussion paper for Capone et al. (loc cit).

Wanninkhof, R., and S. Doney, 2000. IGBP-Ocean CO_2 *draft discussion paper for Paris workshop.*

Substantial inputs to the above documents also came from:

OCTET (Ocean Carbon Transport, Exchanges and Transformations) Prospectus. Available at: *http://www.msrc.sunysb.edu/OCTET/Prospectus.html*.

EDOCC (Ecological Determinants of Oceanic Carbon Cycling): A Framework for Research. Report from the EDOCC Workshop Held at Timberline Lodge, Oregon, 13-16 Mar 2000. Available at: *http://picasso.oce.orst.edu/ORSOO/EDOCC/*.

SOLAS Prospectus. The United States efforts in the Surface Ocean Lower Atmosphere Study (US SOLAS). Available at: *http://www.aoml.noaa.gov/ocd/solas/prospectus.html*.

OVERVIEW AND OBJECTIVES OF THIS COMPONENT

For 1,000 years before the Industrial Revolution, the atmospheric concentration of CO_2 was tightly bounded between 274 and 283 ppm. Such highly constrained boundaries require strong stabilizing feedbacks in the global carbon cycle. The emergent pattern of increasing atmospheric CO_2 in this cycle reflects the balance of fluxes between the oceanic, atmospheric and terrestrial carbon pools and a mix of physical and biological processes. However, our comprehension of the processes that control atmospheric CO_2, carbon fluxes, and the feedbacks that constrain them, are inadequate. Within the past 200 years, anthropogenic activities have led to a secular increase in atmospheric CO_2 with levels climbing above 365 ppm. Whether this increase and that of other "greenhouse" gases will have any substantial climatological effect is at the centre of the major international policy debate. In order to model and predict the consequences of this change in the global carbon cycle it is critical to understand the role of the ocean carbon cycle in modulating future changes in atmospheric CO_2 and climate.

While our understanding of the oceanic C cycle has improved dramatically in the last decade, we have a considerable distance to go before we can predict the probable response of oceanic carbon biogeochemistry and of the oceanic biota to climate forcing induced by atmospheric CO_2. Similarly, we still have not developed the capability to address the physical, chemical, and biological feedbacks to atmospheric CO_2, particularly at the scales of the global ocean. One of the critical components needed to answer these questions is an improved understanding of the past and present temporal and spatial variability of the ocean carbon cycle, especially as it relates to the air-sea exchange of carbon. Credible projections of the ocean carbon cycle response to climate perturbation will not be possible without a much more detailed, mechanistic understanding of the processes controlling the global sequestration of carbon, both natural and anthropogenic. This requires an understanding and quantitative description of the mechanisms controlling fluxes and transformations of ocean carbon.

Accordingly, the overall goal of a new process studies component of ocean carbon research is to improve our mechanistic understanding of biological, chemical, and physical processes that control oceanic [and ultimately atmospheric] CO_2 levels. This overall goal can be approached by posing several questions about the ocean – atmosphere exchanges, transformations and transports of CO_2 and their responses to climate change:

- How is anthropogenic carbon dioxide (CO_2) taken up from the atmosphere into oceanic surface waters and then exported for storage in the deep oceans?
- How will global climate change and CO_2 storage cause changes in the physics and chemistry of the oceans, including future changes in the uptake and storage of anthropogenic carbon dioxide?
- How will marine biota and ecosystems respond to climate change, *e.g.*, changes in ocean stratification as well as warming, and changes in ocean chemistry caused by increased CO_2 uptake?

During our discussions, two important themes arose repeatedly. 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 locate new process studies, where and when possible, in the context of existing or new time series observatories (attended and/or autonomous). To recognize the large-scale aspects of biogeochemical processes, we include a basin-scale component in this report. While individual process studies will almost always be conducted at local to regional scales, they should be embedded in basin-scale studies informed by surveys and remote sensing. Finally, process studies and surveys alone cannot provide definitive answers. Thus, another primary goal of process studies is to inform future models. The questions already stated can be rephrased as:

- What are the critical processes that must be understood in order to model the current regional-to-basin scale distributions of CO_2 uptake/release and carbon export/storage to predict their responses to climate-driven changes in circulation and chemistry?

In the following document we outline some of the specific problems and approaches, which should be addressed in a future, integrated study of the global carbon cycle.

BACKGROUND AND SPECIFIC RECOMMENDATIONS

The anthropogenic (or excess) CO_2 uptake signal is superimposed upon the large background dissolved inorganic carbon (DIC) gradients within the ocean driven by natural physical and biological cycles that in turn have significant natural variability operating on daily to decadal timescales. 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, due for example to global warming, changing carbonate chemistry, or altered [trace] nutrient deposition into the ocean by aeolian transport and continental input. Process studies and modelling efforts are necessary to elucidate these differences.

Our current large-scale understanding of carbon uptake is implicitly grounded in the dogma of a steady state carbon cycle with fixed stoichiometry between biologically mediated processes and inorganic carbon species. The validity of these assumptions is dependent on the scales of investigation. For global scale processes, steady state assumptions often yield reasonable results. At decadal and shorter time scales such assumptions can lead to major misinterpretation of the processes while the question for the centennial time-scale relevant to climate change is not well resolved. The causes of temporal and spatial variability are often partitioned into a biological pump and a [physical] solubility pump. Although conceptually satisfying, the biological and physical processes are intricately linked. For instance, large-scale ocean-atmosphere reorganizations such as PDO, NAO, and ENSO appear to have a significant influence on biogeochemistry (for instance, the Pacific regime shift from P to N limited environments) and ocean circulation. These changes will result in shifts in the dominant plankton groups in various regions. Major changes in the dominance of phytoplankton species are in fact already being observed, notably in the sub-Arctic region. Here the shift from diatoms to *coccolithophoridae* in the Sea of Okhotsk, with parallel collapse of the salmon fisheries, is a dramatic example of global change already taking place.

Physical Processes in relation to the carbon cycle

The process of invasion of atmospheric CO_2 into the deep ocean is sometimes divided into “biological” and “solubility” pumps (Volk and Hoffert, 1984). The biological pump is realized as the sinking of biogenic particles from the surface to the deep ocean, where remineralisation regenerates the CO_2 away from the atmosphere. The solubility pump operates due to the overturning of the oceans, by which dense water sinks out of the surface layer, taking CO_2 absorbed from the atmosphere into the deep sea. Likewise, there is a return flux from the deep to the surface that can carry CO_2 released at depth back into contact with the atmosphere. The contribution of ocean physics to uptake of CO_2 is very substantial, and an improved understanding of the processes determining the overturning circulation is critical to a better prediction of the ocean sink for CO_2.

Some characteristics of the ocean circulation are particularly important to the uptake of CO_2, but are not well modelled by current ocean GCM’s. These include upwelling and subduction of water, the rates at which water exchanges between the deep and surface oceans, between sub-polar and subtropical gyres, depths and extents of convection, and small-scale mixing. GCM’s in current use represent well the characteristics of the surface, wind-driven circulation at the gyre scale. Higher resolution versions, which we can anticipate will be in use for biogeochemical studies within a few years, can produce realistic-looking eddy fields. However, these aspects of the circulation are only part of the story, and not perhaps the most important part from the point of view of the carbon cycle. Many of the processes that actually cause the ocean to overturn will have to be parameterized even in eddy-resolving models.

Current experience with carbon cycle models suggests that improved knowledge of these processes, more than any other single factor, would improve our confidence in the prediction of the oceanic carbon sink over the next century. Plainly therefore, a programme of process studies to learn more about these mixing processes is needed to improve the models.

The great majority of atmospheric CO_2 penetration into the ocean occurs because the ocean mixes and overturns – the 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 near future. The main processes are:

Convection. Convection in the ocean occurs downwards from the surface, on a horizontal scale of a few hundred meters. It is a complex phenomenon that may involve entrainment of water from mid-depth into the convective column, joining of individual columns, and interaction with the larger circulation. Most OGCM's simulate convection only on the grid scale – hundreds of kilometres, and consequently grossly overestimate the mixing that occurs due to convection and the extent of the convection.

Entrainment: Entrainment of one water mass into another occurs adjacent to convective columns or in rapid flows caused by topography. This process is responsible for much of the transport in the thermohaline circulation. For example, it is estimated that the volume of North Atlantic deep water grows by about a factor of three due to entrainment of water into the rapid overflows from the Nordic Seas at the Greenland-Scotland ridge. This is a small-scale process that can only be parameterized in existing GCM's.

Diapycnal mixing. It has been recognized for decades that the magnitude and distribution of small-scale diapycnal mixing in the ocean has a profound effect on the overall circulation. How the ocean mixes is however still unknown. What is known is that it does not mix uniformly everywhere. There are two possibilities. It could be that rapid mixing in "hotspots" near boundaries and other topographic features is responsible for nearly all the mixing. Alternatively, it is possible that virtually the only important mixing is at the surface. In either case, the effects of the locally intense mixing are transmitted to the rest of the ocean by rapid along-density ("isopycnal") mixing and advection.

Key problems for further research

The way in which the above processes are parameterized in ocean carbon cycle models has a first-order effect on their behaviour, the extent to which they match the existing thermohaline structure and predictions for the future. It is generally believed that older, coarser-resolution models are too diffusive, and the introduction of new parameterization schemes such as the Gent-McWilliams parameterization is improving this situation. However the improvements in knowledge required to put the models on a sound intellectual footing will require not just new computer schemes but new studies in the ocean to elucidate the mechanisms involved. These studies should be combined, if possible, with time-series station locations and with biogeochemical process studies. They should include:

Studies of turbulence regimes in different parts of the ocean. Further investigations of the relation of mixing to forcing from the surface or by interaction with topography, using tools such as velocity microstructure, devices to measure Richardson number and tracer release experiments, are required.

Studies of convection and its forcing. In recent years, there have been studies of convection in the Labrador seas and Greenland Seas, which have taught us much about these regions. From the point of view of the carbon cycle, it seems the most important region to understand better is the Southern Ocean however.

Studies of cross-frontal mixing. Horizontal and vertical mixing processes that result in mixing of density classes are interlinked and may have similar effects on the overall thermohaline circulation. Current OGCM's do not resolve fronts well and cannot therefore properly address mixing across them.

The solubility pump

In spite of the continuous rise of CO_2 in the atmosphere, the oceanic surface waters on average tend to be undersaturated *versus* the air and this would lead to net uptake of CO_2 by the oceans. However in reality the dissolved CO_2 in surface waters varies due to seasonal warming and cooling, due to imbalances of photosynthetic CO_2 fixation versus respiration in the plankton ecosystem, and due to upwelling of older, deeper waters. As a result, at any given time the various regions of the world ocean exhibit both over- and undersaturations versus the atmosphere, with changes taking place over a suite of spatial scales (1-100-1000 km) and time scales from days to seasons, years and decades.

For any given position in time and space, the pCO_2 difference between atmosphere and surface waters drives a flux F into or out of the sea according to:

$F = k\ \Delta pCO_2$,

where k is the gas exchange coefficient. We know that k is a function of sea state, the waves and breakers at the sea surface. Wind provides the major forcing of sea state, but the expression of k as a function of wind velocity is known only with about 50 % uncertainty. In addition, several other factors, such as microscale temperature gradients and surface slicks, play a role. Process studies focusing on the mechanism of gas exchange, combining the traditional gradient method of estimating ΔpCO_2 with novel innovative direct flux assessments (eddy correlation, eddy accumulation, and other methodology) are required to be able to better quantify the air/sea fluxes.

As outlined below many of the questions relating to the biological response to changes in [surface] physical processes are often also intricately related to the solubility pump. In broad terms, our mechanistic knowledge of the biological pump is woefully incomplete warranting a strong process-oriented approach. For the solubility pump, we have an understanding of first order forcing and the focus is more on observations of the current state and effect of changing forcing. The inventory and transport observations outlined in Ocean Carbon Observations (p. 9) are in essence investigations of the large-scale solubility pump. In addition, there are surface solubility pump issues that operate on shorter timescales. These can be summarized as:

- What is the present-day exchange of CO_2 and carbon-related properties between the atmosphere and the surface ocean?
- What surface layer processes can alter the future air-sea flux of CO_2 with potential implications for altered sequestration of carbon within the ocean?

The emphasis is therefore 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.

Key problems for further research:

A particular emphasis for the solubility pump on short time scales is the factors controlling the air-sea flux. The improvements in this area include:

- Development of measurement techniques of flux on the same timescales as the variability in the environmental forcing,
- Determine the ΔpCO_2 between the surface skin and the above-lying atmosphere in order to determine k accurately,
- Validate the measurements with conventional approaches,

- Correlate the measurements of k with wind speed,
- Determine if there are better or additional parameters than wind speed to parameterize k in the field, and
- Scale results up to global scale through remote sensing.

The biological pump

The biological pump is the process by which CO_2 fixed in photosynthesis is transferred to the interior of the ocean resulting in a temporary or permanent sequestration (storage) of carbon. Key issues for study of the biological pump include how biological processes affect transport of organic carbon into the oceans' interior, which in turn affects atmospheric CO_2. How much of the interannual variability in the uptake rate can be attributed to the ocean's biological pump? Where is export by the biological pump most significant, and what components of the pump are most important? We must determine the contribution of the biological pump to interannual variability of atmospheric CO_2 and provide greatly improved projections of the response of ocean biogeochemistry to future environmental change and its impact on future CO_2 concentrations.

In recent years there has developed a concept of a background plankton ecosystem of mostly very small nano- and picophytoplankton that mostly recycles the available chemical elements (C, N, P, Fe) within the euphotic zone, creating a retention system. For N the major chemical form is reduced ammonia, which is easily utilised by the cell, as opposed to nitrate, which must be reduced by the iron-rich enzymes, nitrate- and nitrite-reductases. When conditions of light, major nutrients (N, P, Si) and trace nutrients (Fe) are favourable, intense blooms of larger phytoplankton are able to use nitrate (new production). At such times, the major taxonomic groups of diatoms, *Phaeocystis* sp., *Coccolithophoridae* (notably *Emiliania huxleyi*) and N_2-fixing diazotrophs, each in their own manner, are deemed to account for most of the overall biological pump in the oceans. Such changes in the foodweb structure have implications not only for the sequestration of CO_2 into the deep ocean but also in supporting production at higher trophic levels, including species of major commercial fisheries, marine birds and mammals.

Major functional groups (Bloom-forming algae). Diatoms alone account for about a third of all primary productivity in the oceans. Large diatoms can sink out massively at the end of the bloom, when Fe stress affects buoyancy. Phaeocystis sp. blooms have large (100-1000 µm) colonies composed of mucus-like polysaccharides. At the end of the bloom coagulation and aggregation of mucus debris (where bacteria play a role) leads to sinking of organic matter. At the final stages of the blooms of *E. huxleyi*, many loose their calcite coccoliths, leading to export in the carbonate pump. The export term for both organic matter and calcite coccoliths (as found in sediment traps) is largely within faecal pellets of mesozooplankton, a foodweb driven export term.

Shifts in dominant phytoplankton species have implications for global change, and vice-versa. The ratio of photosynthesis versus calcification of *E. huxleyi* has been shown to be a function of the CO_2 equilibrium in seawater. Hence, at increasing dissolved CO_2 in the future, and associated changes of pH, the ratio of photosynthesis to calcification will change. This also applies to symbiotic relationships between photosynthetic algae and large calcifying foraminifera. Both Phaeocystis sp. and *E. huxleyi* are major producers of DMSP, which under suitable conditions is converted to dimethylsulfide (DMS) by bacteria and emitted into the atmosphere, leading to condensation nuclei for clouds, whose albedo reflects solar radiation.

Iron limitation. In recent years, it has been established that iron (Fe) limits biological productivity in 40% of the oceans. Moreover, it is a co-limiting nutrient in vast regions of the remaining 60% of surface waters. Meanwhile the paradigm of a single limiting factor for some or all marine ecosystems has given way to the awareness of co-limitation by several nutrients simultaneously, where light deficiency as well as grazing losses play an important role. So fundamental is Fe in regulating photosynthetic efficiency and electron transport, fixation of CO_2 and overall plant growth, that it is now thought to be intimately linked to atmospheric carbon dioxide and thus, global transitions in climate from glacial to interglacial times. Both in natural conditions as well as during intentional *in situ* Fe enrichments (1995, IRONEX II; 1999, SOIREE), enrichment with Fe was found to stimulate plankton blooms, notably large diatoms, thus also affecting the silicon (Si) cycle of the oceans. Apparently, the relief of Fe limitation leads to a shift up from the recycling small-cell foodweb to the large bloom-forming phytoplankton. Moreover, concomitant drawdown of CO_2 as well as dramatic releases of DMS was reported. The modern oxygenated open ocean is severely Fe-depleted due to continuous removal in solid Fe-oxide forms with settling biogenic particles. However reducing ocean margin sediments likely act as a source of reduced Fe(II) into oceanic waters. On the other hand, in regions with high aeolian Fe input the high cellular Fe requirement for N_2 fixation may be satisfied. The strong occurrences of N_2-fixing *Trichodesmium* in subtropical Atlantic waters appear strikingly consistent with the massive aeolian Fe input from Sahara dust blown over the Atlantic Ocean. The Sahara dust is well documented to vary over decadal time scales, presumably giving rise to decadal variations of N_2 fixation, as tentatively confirmed from Redfield ratio (NO_3 / PO_4) variations observed near Bermuda. Variable atmospheric Fe input may cause significant variations in the budgets and of C and N in the oceans, and air/sea exchange fluxes of CO_2. Currently the Sahara dust accounts for half of all dust Fe input into the global oceans.

Dissolved organic matter. Second in mass to the oceanic dissolved inorganic carbon (DIC) pool is dissolved organic carbon (DOC) (680 PgC in the ocean). This pool of carbon comprises a wide range of organic compounds, most not readily identified by chemical composition, with a wide range of life times. DOC is largely released to the water column as a by-product of primary and secondary production, where it in turn supports microbial metabolic requirements. These products normally turn over on the time scale of hours to days, thereby driving the microbial loop. A small fraction of the DOC produced accumulates for longer periods, thereby becoming important as a reservoir for carbon. DOC accumulates during periods of net community production, with perhaps 20% of the net production fluxing into this pool. Once the carbon is locked into DOC, upper ocean circulation can move it great distances in ocean basins over relatively short (weeks to months) periods. Transport of DOC-enriched surface waters to sites of mid and deep ocean ventilation results in the export of DOC to depth, away from the atmosphere, thus contributing to the biological pump. Highly stratified waters normally exhibit the highest DOC concentrations in the open ocean and the lowest rates of particle export. How changes in ocean stratification with ocean warming might change the primary modes of the biological pump (sinking biogenic particles vs. export of DOC with overturning circulation) is unknown.

In addition to carbon, important fractions of the total nitrogen and phosphorus pools in the ocean are found in dissolved organic matter. In the surface waters of the oligotrophic ocean, essentially all of the N and P are found in dissolved organic matter. These pools may then play an important role in driving new production in oligotrophic regions, following the mineralisation of the DON and DOP. This process has received little focused study to elucidate its true importance. In regions of high N_2 fixation, elevated molar ratios of DON and DOP have been shown to occur (with DON being "new" or allochthonous to the system), serving both as an indicator of the fixation process and having implications for elemental stoichiometry in the ocean.

Redfield vs. non-Redfield stoichiometry of organic fluxes [no contribution submitted]

Key problems for further research

- What is the strength of the biological pump and how does it differ between 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 of organic matter produced in the euphotic zone to differ from the metabolic C/N/P ratio of waters in the underlying twilight zone where net regeneration takes place?
- How does the ratio of net/gross production in the euphotic zone depend on sea surface temperature?
- 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?

Basin-scale studies

In order to constrain estimates of carbon storage in the Northern Hemisphere, we must initiate a new, large-scale and long-term series of oceanographic field programmes in the North Atlantic and North Pacific Oceans. An initial emphasis on the North Atlantic and North Pacific Oceans will contribute to broader efforts to quantify regional magnitudes and variability of Northern Hemisphere carbon sinks. Although most focus to date has been on the terrestrial sink there is increasing evidence that Northern Hemisphere oceans contribute significantly to the total strength and variability of the sink.

A longer-term focus is to determine the role of the ocean carbon cycle in amplifying or ameliorating natural and anthropogenic variation in atmospheric CO_2, and thus climate change. The Southern Ocean is thought to be key in this regard. An important outcome will be an assessment, based on more detailed process-level understanding, of proposed mechanisms by which the ocean carbon sink evolves in the future.

Recommendations for future basin-scale studies

North Atlantic Ocean

- Continue time-series observations at the BATS and ESTOC sites, solidify its core support and augment the routine measurement suite.
- Initiate new time-series sites along latitudinal gradients and a network of autonomous, moored time-series nodes.
- Design and implement a new basin-scale survey programme optimised to improve estimates of the size and interannual variability of the carbon.
- Design and implement a new process study to estimate the contribution and interannual variability of the spring phytoplankton bloom to annual carbon storage, and to determine the

importance of active nutrient transport and nitrogen fixation in the supply of nutrients to the euphotic zone.

- Use new studies of the North Atlantic Oscillation to understand the potential for climate change-induced modifications in the carbon cycle.
- Coordinate with parallel efforts involving studies of the distribution of CO_2 and related tracers in the atmosphere, which are aimed at constraining basin-scale carbon fluxes and their interannual variability.

North Pacific Ocean

- Continue time-series observations at the HOT and KNOT sites, solidify its core support and augment the routine measurement suite.
- Initiate time-series sites along latitudinal gradients and a network of autonomous, moored time series nodes.
- Design and implement a new basin-scale survey programme optimised to improve estimates of the size and interannual variability of carbon sources and sinks.
- Design and implement a new programme of surveys and process studies focussed on improving estimates of the magnitude and interannual variability of nitrogen fixation rates, denitrification rates, and upper ocean carbon fluxes.
- Design and implement a new process study to determine the importance of active nutrient transport and nitrogen fixation in the supply of nutrients to the euphotic zone.
- Initiate a new programme of cruise-based observations and moored-sensor deployments to determine how carbon fluxes and ecosystem structure respond to physical variability on ENSO and PDO time scales.

Southern Ocean

- Establish mechanistic relationships between biogeochemical parameters and environmental boundary conditions.
- Incorporate evolving hypotheses concerning linkages to the state of the tropical oceans, as steps toward understanding the response of Southern Ocean biogeochemical systems to climate change.
- Emphasize development of time-series observations by exploiting ships of opportunity crossing the Southern Ocean (*e.g.*, the regular transit of research vessels across the Drake Passage en route to the Antarctic Peninsula and those crossing the SW Pacific sector to the Ross Sea).
- Explore collaboration with nascent initiatives in France and Australia as a mechanism of implementing early time-series observations of seasonal and interannual variability on which to build later process studies.

Ocean margins

We need to configure a series of ocean margin studies designed to resolve the contribution of continental margin processes to basin and global scale carbon dynamics. These studies should aim to improve numerical model parameterization of margin processes, and should be conducted in a manner that is fully integrated and coordinated with process studies. Recently, biogeochemical studies on continental margins have suggested that margin environments are active sites of carbon and nutrient cycling, and that biogeochemical processes there may influence the ocean carbon cycle as a whole. Estimates of global production conclude that continental margins play a key role in the global carbon budget. Annual new production integrated over the world's continental shelves and slopes is estimated to be over 56% of the total global new oceanic production. High production along continental margins is likely to result in substantial sequestration of carbon, as sinking particle fluxes near margins at any depth are about 10 times larger than seen in the deep sea at similar depths. Globally, at least 44% of the particulate carbon that falls below 1,000 m is derived from the slope and rise of continental margins. The importance of the vertical flux of particles along margins lies in its efficient sequestration of elements. In this sense, the "biological pump" is more significant here than in the ocean's interior. Along margins, natural and anthropogenic perturbations may also have an amplified effect on nutrient supply rates because of vigorous exchanges of energy and matter between land, atmosphere, and the ocean.

Although dwarfed by the air/sea CO_2 exchange fluxes, riverine fluxes alone are of the same order of magnitude as the net air-to-sea CO_2 transfer. These findings suggest that continental margins constitute important but often-neglected links in the global carbon cycle. The phenomenon of the shelf sea serving as a CO_2 sink is sometimes called the “continental shelf pump”. Numerical models do not resolve the various scales of cross-shelf nutrient and CO_2 transport processes associated with upwelling, mixing, or river discharge phenomena along margins. Therefore, these models do not quantify either outgassing or the sinking flux of organic particles associated with such "new" nutrient sources. For example, riverine input and non-point source discharge from continents accounts for about 0.6-1 PgC yr^{-1} transfer of organic and inorganic carbon into the marginal seas. Limited evidence suggests that currently most of this material is either trapped on the margins or transported in localized events to the pelagic ocean.

Key issues relevant to global scales

- What are the magnitude and mechanisms of the carbon sinks and sources in coastal and continental shelf zones?
- What is the fate of the carbon that enters the marginal seas?
- How will these fluxes and transformations change due to large perturbations in coastal zones, in the ocean's interior, as well as due to land use change?

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WORKING GROUP 3

DIAGNOSTIC MODELLING

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INTRODUCTION

Given the large inherent space and time variability of the inorganic carbon system in the ocean, the ability to directly observe and document such variations necessarily will remain limited. As a consequence, reaching the goal of characterizing the regional to global distribution and seasonal to decadal scale variability of carbon sinks and sources in the ocean from observations requires the use of interpolation, extrapolation and other diagnostic techniques. Correlations of pCO_2 with sea-surface temperature have been used successfully in the tropical Pacific to inter- and extrapolate the sparse data to the entire domain (Loukos *et al.*, 2000). However, such statistical correlation techniques work less well in the extra-tropical regions, where a substantial amount of the pCO_2 variability is driven by complicated, since generally opposing interactions of ocean biology with heat fluxes, mixing and transport. In addition, correlation techniques do not allow a gain in understanding the functioning of the ocean carbon system and are therefore of limited usefulness. Alternative options are to use objective mapping techniques or extrapolation techniques derived from the flow field of the surface ocean [Takahashi *et al.*, 1995, 1997, 1999]. However, the use of such techniques is essentially limited to producing climatological distributions, and can therefore not be used to produce reliable estimates of the state of ocean carbon system at any given point in time.

On the other hand, the planned future ocean carbon observing system will be embedded in a larger ocean observing system, generating a wealth of other observations that are relevant and linked to the ocean carbon system, but not necessarily in a direct statistical way. This represents an opportunity for diagnostic numerical models and (more formally) data assimilation schemes, since they are optimally suited for bringing together the diverse set of observations and produce a best estimate of the state of ocean carbon system and of the basin-scale air-sea CO_2 flux. These approaches have the advantage over the other techniques that they produce these estimates in a dynamically consistent fashion and do not rely on statistical correlation, which are limited in their applicability. They also provide rigorous estimates of uncertainties on the inferred quantities.

In addition to the time-space interpolation of limited field and remote sensing data, diagnostic and assimilation models can produce at the same time quantitative estimates of large-scale physical and biological carbon fluxes, estimate optimal parameters, help to prioritise process studies, and provide an assessment of critical gaps in the networks and in the current understanding of the ocean carbon cycle.

DIAGNOSTIC OCEAN CARBON CYCLE MODELING

The main aim of diagnostic modelling is to produce a “best” estimate of the present or past state of a system (“nowcast” or “hindcast”). This goal is achieved by introducing observations into a numerical modelling framework and then adjust parameters, functional relationships, initial conditions or boundary conditions in such a way that an optimal fit between modelled conditions and observed conditions is reached. When the combining of data and models is done in a mathematically formal manner, one often refers to data assimilation or inverse modelling.

Diagnostic modelling therefore provides a natural framework how the different elements of ocean carbon cycle research (observations, process studies and modelling) can be integrated to address some of the overarching questions (**Figure 1**).

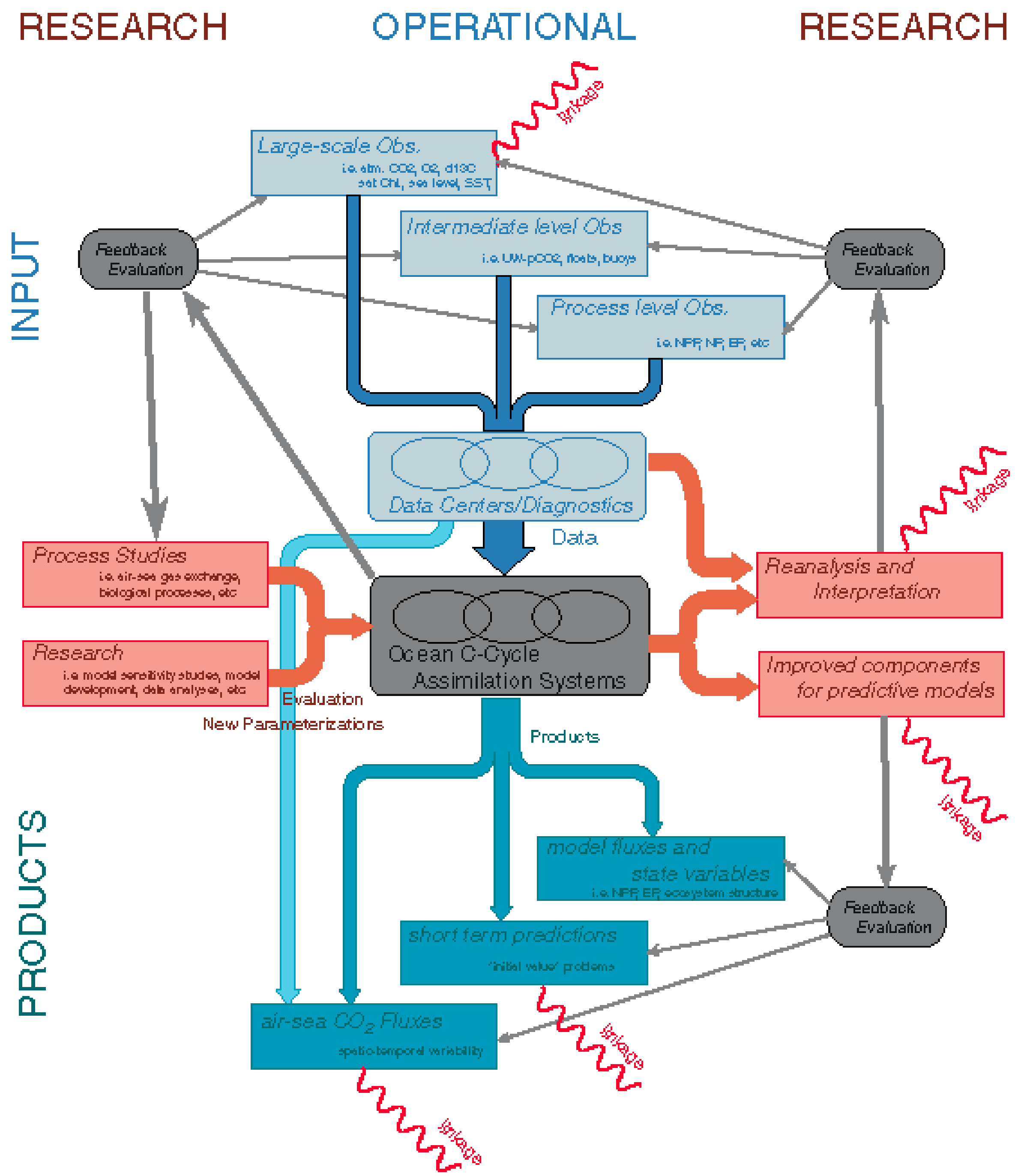

Figure 1: Conceptual diagram of the proposed diagnostic modelling framework. At the centre is an array of diagnostic models integrate the different types and spatio-temporal resolution of the data into their model and produce "best" estimates of the present and past state of the CO_2 fluxes across the air-sea interface and of the state of the carbon system in the ocean in general. The preparation of the data that stream into these diagnostics need the establishment and support of dedicated data centres that collect the data, perform additional quality control and provide long-term availability of these data, *etc*.

Such diagnostic mathematical methods have only very recently begun to be used in global carbon cycle research, despite their long-term application in related fields, such as meteorology, physical oceanography and seismology. Although a large variety of mathematical tools exists to address such diagnostic modelling problems, expertise to judge which method to apply to a particular problem is scarce. It is therefore imperative that resources are allocated to develop and test different schemes on a variety of temporal and spatial scales, making use of a large variety of data.

Diagnostic modelling of the ocean carbon cycle is needed for many purposes. These purposes include the optimal estimation of the state of the oceanic carbon system, the design of optimal networks, parameter estimation, evaluation of process parameterizations and the elucidation of critical gaps. Each of these areas is now discussed in turn.

Optimal estimation of the air-sea CO_2 fluxes

Fully documenting the large space-time variability of inorganic carbon in the ocean and of the fluxes between the different reservoirs will remain very difficult with an ocean carbon observation programme solely based on direct measurements, since any network will remain sparse when confronted with the large amount of variability present in the system. Diagnostic carbon cycle models provide one of the few means how dynamically consistent fields of data from such a sparse network can be generated. The fully resolved four-dimensional data products generated from these diagnostic models will provide the input needed for scientific and political assessments of the state of the ocean and its role in the global carbon cycle. This product can also serve as initial conditions for short-term and long-term predictions using prognostic models.

Design of optimal networks

Diagnostic models represent ideal tools to investigate the most cost-effective measurement networks and observational strategies.

Parameter estimation

Many parameters in predictive ocean carbon cycle models are poorly known. Diagnostic models provide a framework for finding those parameters that result in an optimal fit to the data constraint.

Evaluation of process parameterizations

A large number of processes in ocean carbon cycle models cannot be represented mechanistically, either because they are too complex or poorly understood. This requires the development of parameterizations that attempt to represent the dynamics of these processes without resolving them explicitly. Such new process parameterizations can be ideally tested in inverse models, as they provide an objective measure of the skill of one parameterization over another.

Provide hierarchy of critical gaps

Diagnostic models provide a natural framework for determining and prioritising the critical gaps in the observational networks, in the representation of the key processes, and in the inverse/assimilation methods themselves.

LIMITS OF DIAGNOSTIC MODELING

While attractive in principle, it is important to recognize the limits of diagnostic modelling approaches. The first and foremost limitation is that the results of diagnostic models can only be as good as the quality and quantity of the input data and as the quality of the underlying model. It is therefore important to view diagnostic models as a tool and not as a black box that produces the right results as a long as it is forced with real data. Secondly, diagnostic modelling is, by principle, backwards-looking and the temporal scales of relevance are those that are accessible through direct observations or proxies. Such models are therefore not necessarily the best ones to be used for long-term predictive studies, since entirely different processes can become important on such time scales. Nevertheless, there exist large synergies between diagnostic and prognostic modelling, which should be fully exploited.

CURRENT STATUS

The application of diagnostic modelling techniques to ocean biogeochemical cycles is a relatively novel development, and therefore only a relatively limited number of studies have so far been conducted. An excellent overview of the status of inverse modelling in biogeochemical systems in general is given in Kasibhatla *et al.* (1999).

Among the first oceanic inverse applications were initiated by Carl Wunsch and colleagues (Rintoul and Wunsch, 1991), who used inverse box models to determine the transport of tracers across hydrographic sections. This technique was developed by physical oceanographers to study the transport of mass and heat but was soon also employed to study the transport of biogeochemically relevant tracers as well. This approach and many variants of it has been used by a number of investigators (*e.g.* Ganachaud and Wunsch, 2000; Holfort *et al.*, 1998; Robbins *et al.* 1994), since it is computationally inexpensive, it is independent of a numerical model and it allows to determine not just the transports, but also the sources and sinks of these tracers. However the approach is limited to the determination of the transport just across the measured transect, and often steady state has to be assumed for combining different transects to infer sources and sinks.

An alternative approach is to use Green’s function, widely employed in atmospheric inverse modelling studies, in which a numerical model is used to determine the relationship between cause (mostly fluxes at the boundaries) and effect (changes in interior concentrations) (see Enting, 1999). Gloor *et al.* (submitted) demonstrated how this approach could be used to determine air-sea heat exchange and Gruber *et al.* (submitted) applied it to estimate air-sea fluxes of oxygen. However the Green’s function approach is limited in the general applicability because it to a lesser degree useful to determine interior sources and sinks, and it has to assume that the circulation is perfectly known

Both these limits can be overcome, in principle, by using an adjoint method, which represents one of the most formal inverse modelling techniques (Giering, 1999). An adjoint models is a companion model to a forward (prognostic) model and computes very efficiently the sensitivity of a few model output variables with respect to arbitrarily many input variables. This method has been applied with success to address a number of ocean biogeochemical problems, including air-sea CO_2 exchange and new production (Schlitzer, 1989; submitted) the role of DOC (Matear and Holloway, 1995), and surface boundary conditions (Winguth *et al.*, 1999). The recent development of computational differentiation (Giering, 1999) has made this approach even more attractive. However, adjoint modelling is computationally expensive, permitting only limited studies of parameter sensitivity.

Adjoint models are also increasingly used for biological parameter estimation (Lawson *et al.*, 1996; Spitz *et al.*, 1998; Gunson *et al.*, 1999; Schartau *et al.*, 2000). The common problem in the estimation of these poorly known biological parameters is to minimize a cost function expressing the misfit between the model and the data. It is then argued that, at the minimum of this cost function, one has found the model parameters most likely to reproduce the given data. However adjoint models are not necessarily the "best" method for solving strongly non-linear problems, and other gradient descent methods such as approximate gradient information (Evans and Fasham, 1995; Evans, 1999) have been proposed. An alternative approach employs statistical minimization algorithms that do not require the computation of the cost function gradient but usually require more iterations (Matear, 1995; Hurtt and Armstrong, 1996,1999).

In summary, first steps in diagnostic modelling have already been taken, and various approaches have been applied, but no clear approach or group of approaches have emerged yet as being superior to other ones.

The increased future availability of *in situ* carbon data in conjunction with observations from space together with the great need for data products from policy makers, researchers and other users, provides a great opportunity for diagnostic modelling in the near future. Despite being relatively novel, these diagnostic methods have demonstrated their feasibility and their utility to address some of the large questions in ocean carbon cycle research. At the same time, many important questions about diagnostic modelling are unresolved and require a substantial research effort.

COMPONENTS OF A DIAGNOSTIC MODELLING FRAMEWORK

The components of the proposed diagnostic modelling framework and how they interact with the other elements of an integrated ocean carbon cycle research plan are depicted in **Figure 1**. The two central components are formed by the ocean carbon data centres and the ocean carbon assimilation systems. Together they provide the structure by which the data streams originating from the various observation platforms are collected, assimilated and turned into higher-level data products. In the long term, such a structure needs to become operational in the sense that their operation is carried by institutions with secured long-term funding (such as government agencies) rather than by individual scientists. However, it is important to recognize that the exact nature and structure of such a diagnostic modelling framework is an open question that requires fundamental research. Pilot studies that investigate the methods, data needs, and assess the general feasibility need to be undertaken.

Ocean Carbon Data Centres

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).

Ocean Carbon Assimilation Systems

The core of the diagnostic modelling framework consists of an array of diagnostic numerical models. These models can range in their spatial coverage from regional to global, and can be of various complexities in both their mathematical framework as well as in their biogeochemical representation as needed for addressing a particular need. The development of a diversity of approaches and models is strongly encouraged, which then can compete against each other for various applications. It is envisioned that in the long-term, as these systems will become operational, the most successful systems will be selected and further developed. In addition to these operational systems, diagnostic models will continue to play an important role in addressing research questions associated with network optimisation, parameter estimation studies, *etc*.

Products, Users and Feedbacks

The main product of such a diagnostic modelling framework is 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. Additional products are optimal estimates of all state variables and fluxes that are resolved in the diagnostic numerical model. This includes, but is not limited to, net primary production, export production and standing stocks of inorganic and organic carbon. Four groups of users can be identified: Firstly, researchers, using these data for reanalysis projects, planning and performing process studies, and doing global carbon cycle analysis. The latter research includes atmospheric inversion studies, terrestrial biosphere modelling through providing constraints on air-land biosphere CO_2 exchange fluxes, atmospheric modelling, and coupled climate models. Having a diagnostic framework in place allows researchers also to add other atmospheric trace gases, such as DMS, N_2O, *etc.*, at very little extra cost but with maximum value (value added products). The second group of users is policy makers that need estimates of the seasonal and annual fluxes of CO_2 into and out of all components of the global carbon cycle for assessment studies of the fate of the anthropogenic CO_2. The third group is fisheries, which can improve their fisheries management efforts by having better estimates of the distribution and variability of primary and export production in the ocean and on the continental margins. The last group of potential users includes other government agencies, which are interested in marine optics, *etc.*

An important benefit that emerges from the use of such a diagnostic modelling framework is that they provide, through analysis of the misfit between the model and the observation, a formal way for evaluating the quality and quantity of the data, for assessing the adequacy of the processes implemented in the models and for investigating the overall quality of the model structure. The development of such feedbacks has to be encouraged and supported. At the same time, the diagnostic models have to remain flexible, to make optimal use of new data streams, new parameterizations and new developments in the mathematical concepts of inverse/assimilation modelling.

LINKS TO OTHER COMPONENTS OF THE INTEGRATED PROGRAMME

Links to Other Elements of the Ocean Carbon Cycle

The proposed diagnostic modelling framework represents a natural way to couple the different components of an integrated ocean carbon cycle research programme. It integrates the data obtained from the observational networks with a numerical model to produce a best estimate of the state of the ocean carbon system. At the same time, analysis of the results yields information how the network can be optimised. Strong interactions exist also with the process studies in that improved parameterizations can be readily tested in a diagnostic framework and the skill can be objectively determined by the data model misfit. The diagnostic modelling framework can help to determine the critical gaps in the understanding of the current carbon cycle and identify which critical processes need to be studied with highest priority. The constant evaluation of the model against observations constitutes a strong impetus for improving the skill of these models and therefore can provide the prognostic modelling framework with well-tested physical and biogeochemical modules and elements. In many cases, the synergies between diagnostic and prognostic modelling might even go further, in that the same numerical models that are used for diagnostic modelling can also be used for prognostic modelling.

Links to Other Elements of the Carbon Cycle

In the short term, the strongest linkage exists with atmospheric inverse modelling efforts, as the estimated air-sea fluxes of carbon provide a powerful constraint on the atmospheric inverse problem and thus on the estimation of the exchange fluxes between the atmosphere and the terrestrial biosphere. In the intermediate term, the linkage between the land surface and the ocean through rivers needs to be investigated and established. In the long term, the diagnostic modelling of the ocean, atmosphere and terrestrial biospheres need to be merged into a diagnostic assessment of the global carbon cycle.

Links to Other Elements of the Climate System

The ocean carbon cycle is embedded and strongly influenced by its physical turbulent environment, and therefore cannot be investigated in isolation. It is therefore imperative that the diagnostic ocean carbon cycle framework is developed in strong connection with similar activities on the physical oceanographic and climate community side. Such programmes have been initiated a few years ago at the international level, like 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 US 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 circulation 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.

PHASED IMPLEMENTATION

As diagnostic modelling has just begun to be used more widely in ocean carbon cycle research, implementing the structure proposed above requires a phased implementation. We propose three phases: A research phase, an intercomparison and evaluation phase, and a maturing phase. It is anticipated that the timeline for each phase will take about five years.

Research Phase

The first phase should be centred on the development of pilot projects that will examine and test the feasibility of various diagnostic-modelling approaches. As large amounts of data are already available from past efforts (satellite chlorophyll, satellite SSTs, altimetry, underway pCO_2, hydrographic survey data), these pilot projects do not have to wait until the data from the newly developed ocean carbon observing system begin to flow. Most likely, the pilot projects will consist of studies using coarse resolution models, focus on basin rather than global scales, and will have to link very closely with related efforts on the ocean circulation problem (*e.g.*, GODAE).

Strong emphasis should be given to promote diversity, exchange and interactions. The latter could be fostered through the organization of summer/winter schools, where young scientists are exposed to the tools and techniques of diagnostic modelling.

Equally important to the development of the diagnostic models themselves is the establishment and support of data centres for collecting and archiving the data streams that are currently lacking one or for data that will become available in the near future with the advancement of new technologies. Synergies with existing data centres, such as CDIAC (Carbon Dioxide Information and Analysis Center), NODC (National Oceanographic Data Center), WOCE hydrographic data centres, and the JGOFS national data centres, should be used to the largest extent possible.

Intercomparison/Evaluation Phase

As the initial hurdles of developing and applying diagnostic models have been overcome, and a number of promising approaches have emerged from the first phase, these models should be inter-compared against each under a common protocol. As experience with other intercomparison projects has shown, this will promote the further development of these models as strengths and weaknesses are clearly exposed. Incorporation and vigorous testing of new parameterizations developed from the process studies needs to be promoted, as well as the exchange of these developments with the prognostic modelling efforts. First studies on network optimisation should be performed and fed back onto the structure of the observing system.

Maturing Phase

It is envisioned that in the diversity of approaches that has been promoted and supported during the first two phases will slowly diminish, as superior approaches will emerge and other approaches will disappear or used only for very particular problems. During the maturing phase, the core of the diagnostic modelling should make a transition from research done by individual scientists or group of scientists to operational application performed by institutions with secured long term funding. This should ensure the long-term support of this diagnostic modelling framework, which is very difficult to achieve by individual scientist driven research. It is also envisioned that the ocean carbon cycle diagnostic modelling framework will become part of a global carbon cycle diagnostic modelling framework that assesses the fluxes of CO_2 in and out of all-important reservoirs simultaneously.

CRITICAL GAPS

The most critical gaps for starting the development of such a diagnostic modelling framework are the following:

Feasibility: How feasible and cost-effective is such a system? How fine does the resolution of the underlying model have to be, and how complex is the ecosystem?

Mathematical methods: What are the best methods for introducing observations into a numerical model? Simple data nudging is very dangerous since it introduces sources and sinks of tracers without necessarily mass conservation and it does not allow improving the knowledge of the underlying processes.

Biogeochemistry model: Successful assimilation of observations into a biogeochemistry model requires this model to predict the state of the observed quantities (*i.e.* chlorophyll, *etc*). As such, models exist only to a limited degree, and this requires speeding the development of biogeochemistry models. A particular problem that needs to be addressed is how the information that is gathered in the process studies can be crystallized most effectively into new parameterizations and then introduced into prognostic and diagnostic models.

Data: What is the best mix of data for these models? What data sets are most informative about the quantities we are interested in? Do the data give us enough information to choose among candidate biogeochemistry models? Are surface observations or deep observations most important? How much emphasis has to be placed on chemical, biological and physical observations? Since diagnostic models are not in place to guide the development of the first ocean carbon observing system, this system will be built without input from diagnostic models.

NEED FOR DIVERSITY

Biogeochemical systems, such as the ocean carbon cycle, are complex in that they consist of a large number of linked entities and processes that can lead to non-linear interactions, multiple equilibria and abrupt transitions. Our understanding of these systems is very limited, and our current ability to capture the relevant processes in a reduced number of mathematical equation even more so. Furthermore, the mathematical concepts for assimilation, while in principle well known, have not been used extensively to address biogeochemical problems, and are therefore largely untested. It is therefore of utmost importance that a multitude of approaches and models by a diversity of researchers are developed and tested on a variety of problems.

SUMMARY

The proposed diagnostic modelling framework provides a natural structure by which the different elements of an ocean carbon cycle research plan can be integrated. However, we are currently far away from having such systems in place, and many fundamental questions have not been addressed yet. This framework therefore constitutes a long-term vision. However, the first steps towards the development of such diagnostic systems should start now in conjunction with the development of a global carbon observation network.

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WORKING GROUP 4

PROGNOSTIC OCEAN CARBON-CYCLE MODELING

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INTRODUCTION

To make informed decisions regarding energy and land-use policy, we need to understand how the global carbon cycle will evolve in response to human activities. Therefore, the oceanic research community must be able to provide reliable predictions of air-sea carbon fluxes, including both their natural fluctuations and their response to human influences. Such a predictive capability depends on the development of models based on mechanistic representations of key processes, carefully evaluated with a diverse set of observations. The primary goals of such modelling will be predictions of (1) air-sea fluxes of CO_2 and other climatically important compounds and (2) impacts of global change on the marine environment.

What is Prognostic Ocean Carbon Modelling?

Prognostic ocean carbon-cycle modelling is the forward, predictive simulation of the ocean carbon cycle and, particularly, its response to increasing atmospheric CO_2 content, climate change, and/or human activities.

Prognostic ocean carbon cycle models depend on having good representations of both ocean biogeochemistry and physical ocean tracer transport. The biogeochemical models are typically mechanistically based models that stem out of detailed process studies. The physical ocean transport fields may come from prognostic ocean general circulation models (either run coupled or in off-line modes), or may be provided by assimilation models.

Coupled Climate and Carbon System Modelling

Coupled climate and carbon system modelling presents a major framework to integrate our understanding of the global system into a tool that can be used to predict the response of the climate-system to human action. To make accurate predictions of future climate change, and the impacts of that climate change, we need to simulate the dynamics of storage and fluxes of carbon within the oceans, atmosphere, and land-surface. It is incumbent on the oceanographic community to provide robust models of the marine carbon cycle for incorporation in such models.

The two major issues facing researchers studying the carbon cycle are (1) to understand the present-day functioning of the carbon cycle, and (2) to predict how the carbon cycle will evolve with changes in climate, chemistry, and human activities.

Assimilation models can provide the unifying framework for addressing the present-day functioning of the carbon cycle. Coupled climate/carbon-cycle models provide the unifying framework for predicting the future functioning of the carbon cycle and its interaction with climate and human activities. A major goal of prognostic ocean carbon-cycle modelling is to provide the oceanic component of coupled ocean/atmosphere/land-surface/sea-ice climate and carbon cycle models.

Why Do We Need Prognostic Ocean Carbon Modelling?

Prognostic ocean carbon-cycle modelling is needed to predict:

Impact of Anthropogenic Carbon Emissions on Atmospheric CO_2. Well-tested prognostic models are needed to predict future air-sea CO_2 fluxes. The oceans are thought to absorb about a third of today's fossil-fuel CO_2 emissions. However, this absorption will become less efficient as the oceans continue to absorb excess CO_2, and may become less efficient in response to climate-induced changes in ocean mixing and circulation (Sarmiento *et al.* 199x).

Impact of Increasing Carbon Dioxide on Marine Ecosystems. Increasing atmospheric CO_2 content will result in significant changes in ocean chemistry, and these changes in ocean chemistry could have significant ecosystem impacts, which could, in turn, affect air-sea CO_2 fluxes. For example, increasing atmospheric CO_2 will result in increased concentrations of dissolved aqueous CO_2 ($CO_2(aq)$). There is some evidence that calcareous plankton are favoured in environments in which calcification is an effective strategy for increasing cellular absorption of CO_2. With increasing [$CO_2(aq)$], calcareous organisms could be out competed by other planktonic groups. This would result in greater alkalinity in surface waters, which could lead to increased oceanic carbon uptake. The study of the effect of the impacts of chemical changes in the marine environment has been largely unexplored, but could prove to be important both in terms of direct environmental impacts and for its impact on the global carbon cycle. For example, using the Hamburg Ocean Carbon Cycle model, Kleypas *et al.*, (1999) predict that the biogenic precipitation of aragonitic reef building corals will decrease by 14-30%, due to increasing ocean acidification. The impact of the change in acidification on nutrient and carbonate utilization by marine life must be more thoroughly studied.

Unintentional Human Impacts on the Marine Carbon Cycle. Human-induced changes in river fluxes, coastal pollution, and fish stocks may each affect ocean biogeochemistry, and thereby have indirect effects on the carbon cycle. The impact of these and other factors on marine biota and the ocean carbon cycle are poorly understood, and need to be explored further.

Impact of Purposeful Ocean Carbon Sequestration Activities. Several proposals have been put forth to slow the accumulation of fossil-fuel carbon in the atmosphere by engaging in activities that would increase ocean carbon storage. Funds have been allocated in Japan, the United States, Norway, and the European Union to investigate one or more of these proposals. Proposed ocean carbon sequestration strategies can be divided into two classes. The first class of strategies attempts to increase oceanic absorption of atmospheric CO_2 by increasing the biological flux of carbon from the near surface ocean to the ocean interior, for example, by fertilization of the surface ocean with added iron. The second class of strategies involves direct chemical or physical efforts to increase ocean carbon storage, for example, by injecting concentrated CO_2 directly into the ocean interior. Ocean biogeochemical models need to be developed that can help predict the effectiveness of such proposals, and predict the unintended impacts on both near surface, mid-water, and benthic ecosystems.

The Need to Anticipate Surprises

Preliminary model results indicate that the coupled climate and carbon system may be replete with unanticipated surprises. For example, coupled prognostic climate models indicate that sometime in this century the North Atlantic thermohaline circulation may "shut-down" or the Austral Ocean could be "blocked" by stratification, with significant implications for the global carbon cycle. Chemical changes induced by increasing atmospheric CO_2 could lead to highly uncertain ecosystem changes, which could in turn impact the global carbon cycle. Warming of the ocean may destabilize methane hydrates in the upper sediments releasing large volumes of methane to the overlying water column and perhaps the atmosphere. This potent greenhouse gas could lead to yet more global warming, leading to a positive feedback in the climate system.

We have thought of these few potential surprises, but there are undoubtedly other potential surprises about which we do not yet have an inkling. Prognostic models typically produce unanticipated results. Careful evaluation of these results can help to determine whether the result is a real possibility for our near future, or whether it is simply a model artifact. Prognostic models are tools to help prevent our society from being blindsided by a major unanticipated catastrophe.

RECENT PROGRESS

Recent progress in prognostic ocean carbon-cycle modelling has come in several areas, including consideration of climate/carbon-cycle interactions, representation of the role of micronutrients in limiting phytoplankton growth, representation of ecosystem dynamics, use of newly available data sets and the development of an institutional framework for the Ocean Carbon-cycle Model Intercomparison Project (OCMIP) to improve model diagnosis and evaluation, and renew efforts at simulating purposeful ocean carbon sequestration.

A number of studies have looked at likely effects of global climate change on the ocean carbon cycle, and the impact of ocean carbon cycle changes on global climate (*e.g.*, Joos, Monfray, Sarmiento, *etc*.). These studies have generally indicated that changes in ocean circulation (*e.g.*, increased stratification and slower overturning) lead to less effective oceanic absorption of anthropogenic CO_2. However, with increased stratification and a slower overturning, marine ecosystems may be able to utilize more efficiently nutrients in the surface ocean, which would tend to permit increased oceanic CO_2 absorption. Further advances in prognostic modelling will improve quantification of these effects.

Over the past decade, it has become increasingly clear that micronutrients such as iron play a critical role influencing oceanic carbon fluxes (*e.g.*, Martin). Recently, the iron cycle has been crudely incorporated into a global ocean carbon cycle model (Archer *et al.*). Improved representations of the role of iron and other micronutrients (*e.g.*, zinc) will lead to more reliable predictions of the response of the ocean carbon cycle to both global change and intentional ocean fertilization.

Early ocean carbon cycle models either did not represent biology explicitly (*e.g.*, Sarmiento *et al.*) or represented the effects of biology highly schematically (*e.g.*, Najjar *et al.*, Maier-Reimer). Attempts have been made to move beyond such schematic representations with models that represent the trophic structure of marine ecosystems (*e.g.*, Sarmiento, Fasham, *etc*.). Such models may be more capable of representing the phytoplankton blooms that package carbon in forms that are efficiently transported to the deep ocean. Future modelling efforts in this direction should lead to prognostic ocean biogeochemistry models that can respond mechanistically to changes in ocean circulation and ocean chemistry.

The WOCE and JGOFS efforts have produced datasets required for detailed process studies. These data sets are also critical in the diagnosis and evaluation of ocean carbon cycle models. The Ocean Carbon-cycle Model Intercomparison Project (OCMIP) has been initiated to institutionalise this process. As a result, every major ocean carbon-modelling group is now producing output in a common format, and model results from individual groups are routinely shared with a wider community. Many institutions do not have the resources or inclination to mount a large modelling effort; the openness and data distribution brought about by OCMIP will allow individual researchers and graduate students from such institutions to participate in model diagnosis and evaluation activities.

Interest in slowing the accumulation of atmospheric carbon dioxide has spurred interest in the study of methods to purposefully increase ocean carbon storage (*e.g.*, Sarmiento and Orr, Bacastow and Maier-Reimer). OCMIP has conducted a project comparing the effectiveness of direct CO_2 injection as a carbon sequestration strategy as predicted by several modelling groups. Further work in this direction will lead to improved predictions of both the effectiveness and environmental impacts of proposed strategies dealing with ocean carbon sequestration.

LINKS TO OTHER COMPONENTS OF THE PROGRAMME

Prognostic ocean carbon-cycle modelling has important links to other aspects of ocean carbon-cycle research, as well as links to other components of global change research.

Links to Other Ocean-Based Components

Prognostic ocean carbon-cycle modelling depends on and helps contribute to ocean observational programmes, ocean process studies, and inverse and assimilation ocean modelling.

Links to Ocean Observations. Observations of the ocean, and associated observations in the laboratory, obviously form the foundation of our understanding of oceanic processes and their representation in prognostic models. Furthermore, observations are essential for model evaluation. The data needs for developing process understanding are discussed elsewhere in this document.

Prognostic models can be used to provide guidance for future observations. For example, the Ocean Carbon-cycle Intercomparison Project (OCMIP) has determined areas in which the prognostic model predictions disagree for the current ocean. These results, when compared with the available data coverage, can be used to determine locations in which additional data would most aid in model evaluation and diagnosis.

Communication and openness between observationalists and modellers are essential. We strongly advocate that datasets, once quality controlled, should be made available as quickly as possible to the entire community. Likewise, great benefit has been shown to derive from sharing model output and code and such should be strongly encouraged. Modelling groups (*e.g.*, OCMIP) should provide standardized reference simulations under comparable conditions to facilitate standardized model-data evaluation. Means should be provided for establishing distributed data centres, where observational and model datasets can be accessed easily. Additionally, standard analysis tools should be developed and distributed to encourage such collaboration.

Links to Ocean Process Studies. Reliable prognostic models depend on mechanistically based representations of the underlying critical processes, and prognostic modelling can help determine the most important processes to represent. As such, strong and rapid links should be developed between prognostic carbon-cycle modelling studies and process studies.

On occasion, in the past, process studies developed process representations that were, while much simpler than reality, more complicated than can be easily digested in large-scale general circulation models. It is therefore important that an effort be made to assure that large-scale modellers work with mechanistic-process modellers to develop representations of processes that include the most important factors, while retaining a level of simplicity that permits global or large-scale application.

Sensitivity studies using prognostic models can be used to determine which processes are likely to be most important in influencing future air-sea CO_2 fluxes. For example, the question of whether the change in geographic distribution of various ecosystem types will significantly influence air-sea gas exchange can be approached through a series of sensitivity studies, prior to a thorough effort to simulate such changes. Furthermore, areas in which prognostic modellers fail to adequately represent the real world will suggest processes that are inadequately represented in the prognostic models. In this way, prognostic modellers can help to determine the set of processes that we need to study most critically to reliably predict future air-sea fluxes.

Links to Inverse and Assimilation Modelling. Inverse and assimilation modelling can aid prognostic modelling in several ways. These modelling efforts can provide fields with global distribution that can be used to initialise and evaluate prognostic models. Parameterizations developed for assimilation models can be incorporated, either directly or with modification, into prognostic models. Assimilation models can be of great use in estimating parameters for use in prognostic models (*e.g.*, Prunet *et al.*, 1996a,b; Matear and Holloway, 1995).

Similarly, prognostic modellers will be able to provide assimilation modellers with parameterizations of key processes. Areas in which the prognostic modellers fail to adequately simulate observations will point to processes and regions, which both the prognostic and assimilation models are in need of better process representations. Prognostic physical modellers should be encouraged to work in conjunction with data assimilation efforts using the same basic physical-biogeochemical model. In some cases, the same model may be run in either assimilative or prognostic modes, such that advances directly contribute to both types of modelling effort. However, it must be understood that there are processes that may prove important on the centennial time scale, which may not be important on the shorter time scales considered by assimilation models. For example, long-term changes in the mixed-layer dynamics, the CO_2-buffer-factor, or the effect of changing pH on marine ecosystems may prove important in long-term changes, but may be relatively unimportant on shorter time scales.

Links to Other Components of the Climate and Carbon Cycle

Prognostic ocean carbon-cycle modelling depends on, and should be integrated with, other components of climate and carbon cycle research. Prognostic ocean carbon-cycle modelling has particularly close ties with land surface modelling, atmospheric inverse modelling, atmospheric climate and chemistry modelling, and the human dimensions of global change.

Land Surface Modelling. The ocean receives significant fluxes of nutrients and carbon through rivers and land-based components of the coastal zone. These fluxes need to be incorporated into prognostic models of the ocean. Additionally, the ocean carbon cycle is linked to the land surface through the atmosphere. Therefore, a unified model incorporating the land, atmosphere, and ocean components are needed to make reliable predictions.

Atmosphere Inverse Modelling. Prognostic modelling can help atmospheric inverse modelling by providing independent boundary conditions for air sea fluxes. Conversely, atmospheric inverse modelling can help ocean modelling by providing independent estimates of air sea fluxes that can be used to evaluate ocean carbon cycle models. Regions where divergence of top-down and bottom-up approaches occurs must be key research areas to be more confident in flux patterns.

Atmospheric Climate and Chemistry Modelling. Carbon dioxide is the principal gas of interest to climate modellers. However, carbon dioxide is not the only radiatively important gas to be emitted by the oceans. For example, the oceans release DMS, which is though to have a significant effect on planetary albedo, and therefore global climate. Prognostic ocean biogeochemistry models can provide predictions of changes in fluxes of these gases to atmospheric chemists to help improve predictions of future climate.

Links to Human Dimensions of Global Change. The primary driver of climate change appears to be anthropogenic interference in the climate system (IPCC, 1995). As these human influences affect the ocean, changes in oceanographic conditions can affect human behaviour.

The largest human impact on the ocean may be the impact that occurs through global climate change. However, changes in land-use practices and water use policy may significantly affect river fluxes, with for consequences for the oceanic environment. For example, Mississippi River fluxes have been associated with increased hypoxia in the Gulf of Mexico. More generally, coastal eutrophication may have an increasingly large impact on open ocean environments. Furthermore, over fishing may affect the trophic structure of marine ecosystems, which could potentially have carbon cycle impacts. Looking to the future, purposeful carbon sequestration, through direct releases of CO_2 or through ocean fertilization, could have potentially large and unknown effects on the marine carbon cycle.

Conversely, changes in the ocean carbon cycle could affect human behaviour. Increases or decreases in the efficiency of ocean carbon uptake could affect carbon emissions policies. Quantification of oceanic sources and sinks are essential to help evaluate the potential impact of various emissions mitigation strategies. For example, changes in air-sea CO_2 fluxes could mask the impact of changes in air-land CO_2 fluxes on atmospheric CO_2 content.

RESEARCH FOCUS

The current generation of ocean biogeochemical models contains serious deficiencies with respect to simulating the mean state, natural variability, and potential responses/feedbacks of ocean biogeochemistry to climate change. Parallel development in both biogeochemical and physical ocean modelling are needed to address these issues (**Table 1**).

Table 1. Future Directions in Physical Ocean Modelling

Sub-grid scale parameterizations	**Model resolution and domain**	**Model numerics**	**Data to drive and/or evaluate physical models**
Better representation of turbulent mixing (*e.g.*, role of topography, internal wave breaking)	Higher model resolution.	Better model numerics for advection of momentum and tracers.	Better representation of surface forcing (satellite salinity, wind stress, heat and water fluxes)
Better representation of boundary layer processes (benthic boundary layer, mixed layer)	Adaptive meshes to allow higher resolution where it is needed (boundary currents, deep water formation areas, narrow sills, *etc*.)	Numerical schemes for reduced numerical diapycnal diffusion (isopycnal models?)	Longer time series for the study of variability
Better representation of sea-ice/ocean coupling	Inclusion of the coastal zone	Better collaboration between physicists and biogeochemists to adapt the transport schemes for temperature and salinity to passive tracers	Historical $\delta^{14}C$ (corals, salmon scales, *etc*.)
Representation of unresolved eddies on nutrient transport into the euphotic zone	Acceleration techniques to bring high-resolution models into statistically stationary states.	Lagrangian models (water parcel tracking)	Large-scale data synthesis (^{14}C, CFC, ? CO_2, *etc*.)
	Simulation of interannual variability		

Biogeochemical Model Development

Biogeochemical models are critical to determining air-sea fluxes of CO_2 because surface ocean ecosystems transform dissolved inorganic carbon into forms of carbon that can be transported to the deeper ocean, primarily through the sinking of particulate matter. Some of this carbon export from the upper ocean to the ocean interior is compensated by a CO_2 flux from the atmosphere to the ocean. When carbon-rich parcels of water from the ocean interior are transported to the surface, some of this carbon can degas to the atmosphere. Marine biota can also affect the alkalinity in the surface ocean. Changes in alkalinity change the partial pressure of CO_2 in the surface ocean, and can thereby drive fluxes of CO_2 into or out of the oceans. For these reasons, accurate predictions of air-sea CO_2 fluxes depend on reliable models that represent important processes affecting marine biota and chemistry.

As discussed above, ocean chemistry and circulation will change in response to changing atmospheric CO_2 content and climate. Mechanistic models are needed to predict the response of marine biota to these changes and to predict the impact of changes in marine biota on future air-sea CO_2 fluxes.

Ocean Ecosystem Types. On the land surface, it is clear that there is a need to independently represent tropical rain forests, grasslands, and deserts because these ecosystems affect CO_2 fluxes into and out of the atmosphere in different ways. Similarly, it is becoming increasingly clear that there is a need to represent different ecosystem types in the ocean because these ecosystem types affect air-sea CO_2 fluxes in different ways. For example, ecosystems dominated by diatoms seem to produce rapidly sinking particles that efficiently transport carbon to the deep ocean, whereas ecosystems dominated by organisms with carbonate skeletal material can affect surface alkalinity in a way that tends to drive CO_2 out of the ocean and into the atmosphere.

Marine biogeochemists often use terms such as "functional groups" or "biogeographical provinces" to represent these concepts (*e.g.*, Longhurst, 1998; Sathyendranath *et al.*, 1995), and often talk of the need to represent various genera or species in an effort to get at underlying processes. The motivation for representing this level of detail is similar to the motivation for representing various ecosystem types in terrestrial carbon-cycle models.

However, the situation in the ocean is in some ways more complicated than on land. Due to the long life of trees and other organisms that dominate land ecosystems, the geographic distribution of land ecosystems responds relatively slowly to changing climate, so the geographic locations of ecosystem types can largely be considered as fixed on centennial time scales (with the major exception of land-use changes). However marine ecosystems are typically dominated by organisms with a turnover time of days or less, and the distribution and composition of ecosystems can change rapidly with changing climate conditions. Hence, prognostic ocean biogeochemistry models need to be able to predict ecosystem distributions based on physical parameters and nutrient concentrations.

The Importance of Iron. A number of experiments in which marine organisms or ecosystems have been fertilized with trace amounts of iron have shown that marine biological production is limited by iron in many regions of the global ocean. Iron may also play an important role in the transformation of dissolved inorganic nitrogen into the reduced forms that allow the nitrogen to be utilized as nutrients by marine organisms. While initial studies have demonstrated the importance of iron, the role of iron in the ocean carbon cycle is still poorly understood.

We need further process studies on the role of iron in marine ecosystems and concerted efforts to distill the most important processes into parameterizations that can be employed in marine biogeochemical models.

The Role of Particulate Matter. Particulate organic carbon (POC) and particulate inorganic carbon (PIC; typically $CaCO_3$) are generated by ecosystems in the euphotic zone (the zone in the upper ocean that receives adequate sunlight to support photosynthesis), and then sink into the ocean interior. The sinking of POC tends to drive a flux of CO_2 into the ocean where it is generated; however, when the parcel of water into which the POC remineralised (*i.e.*, is oxidized), is transported to the surface ocean, this tends to drive a flux of CO_2 out of the ocean. PIC, due to its effect on ocean alkalinity, has effects of the opposite sign.

Some ecosystems (*e.g.*, diatom-dominated ecosystems during the spring bloom) tend to generate large amounts of rapidly sinking matter. These ecosystems can transport carbon to the deep ocean where it may be retained for hundreds of years. Other ecosystems (*e.g.*, picoplankton dominated ecosystems of the central gyres) tend to produce small amounts of particles that appear to remineralised in the upper ocean, where the carbon may be retained for months to years.

The factors that control the production and remineralisation of organic matter are poorly understood. In particular, there is extremely little mechanistic understanding of the processes that control the remineralisation of organic and inorganic matter in the ocean interior. Present models typically use empirical relations with little mechanistic foundation. Ultimately, we need process based models of remineralisation. First steps in this direction may involve the development of empirical relations that take into account various oceanic conditions (*e.g.*, supply of ballast, temperature, *etc*.). Ultimately, adequate representation of these processes may require whole ocean ecosystem models (*i.e.*, modelling the ecosystems of the ocean interior).

The Role of Dissolved Organic Matter. Dissolved organic carbon (DOC) is generated by ecosystems in the euphotic zone. Some of this organic matter is mixed or advected downward into the upper thermocline (50 m - 500 m depth), where it remineralised (*i.e.*, is oxidized) into dissolved inorganic carbon and nutrients. This is the secondary pathway by which marine biota transport carbon into the ocean interior. (Transport of particles is the primary biotic pathway, and transport of dissolved inorganic carbon is the primary physical pathway.)

Longer lasting DOC transports carbon and nutrients further from the euphotic zone. This would tend to both store carbon deeper in the ocean interior, and move nutrients away from where they can support photosynthesis in the upper ocean. DOC appears in a heterogeneous mixture of material, ranging from labile organic material that remineralised in days or less to relatively recalcitrant material that may persist for hundreds of years. Most ocean biogeochemistry models (*e.g.*, the OCMIP biotic simulations) represent this organic matter as a single pool with a lifetime of months to years. Clearly, this is inadequate.

The Role of the Sediments. Ultimately, anthropogenic carbon dioxide will be buried in the sediments, primarily in the form of calcium carbonate in corals and lime muds on the sea floor (Archer *et al.*, 1998). However, on shorter time scales, anthropogenic carbon will tend to enhance dissolution of carbonate minerals in the ocean. These minerals can be found not only in the sediments, but also in the carbonate skeletal material and shells of organisms living in the water column and on the sea floor. Effects may be most pronounced in mid-depth waters, where very little is known of the marine biota.

Modelling of sediments also provides a means of evaluating ocean model performance. The geographic distribution of sediments is fairly well known. With a sediment model, we can evaluate whether the fluxes of silica, carbonate and organic carbon predicted by the marine biogeochemical model are consistent with observations. This information can act as a critical test of models of export production in the upper ocean and models of remineralisation and dissolution in the ocean interior.

Physics and Transport Model Development

A major conclusion of the Ocean Carbon-cycle Model Intercomparison Project is that adequate simulation of the carbon cycle depends sensitively on having good representations of ocean physics and tracer transport properties. **Table 1** lists research areas in which physical ocean modelling progress may be made in the coming decade.

The long-term behaviour of simulated tracer uptake by the ocean is very sensitive to advective and mixing processes represented in the model. Therefore, we need to examine the relative roles of mixing and advection in getting the tracers into the ocean. Furthermore, we need to understand better how model numerics (*e.g.*, advection schemes) influence the results of ocean biogeochemical models.

Current prognostic ocean circulation models used to study the carbon cycle study contain serious deficiencies. Critical processes associated with boundary layers, deep-water formation, sea-ice/ocean coupling, and diapycnal mixing occur on spatial scales that will not be explicitly resolved in the near future, indicating that there is a need for creative development of parameterizations of subgrid-scale processes. Furthermore, state-of-the-art global physical models are available that resolve some eddies, but these models are computationally expensive. With current computer capabilities, these models cannot be run for the thousands of simulated years required to "spin-up" global ocean carbon cycle simulations.

This constraint could be partially overcome using highly efficient off-line tracer transport models. Prognostic biogeochemical models could then be used with a complementary diagnostic circulation (for climate simulations without dynamical carbon feedback) or prognostic circulation derived from coupled ocean-atmosphere models (for climate with carbon feedback, see below). Furthermore, such off-line models that can use rapidly new meso-scale physical fields, especially from on-going operational ocean physics assimilation efforts. Of course, results from such off-line models need to be evaluated by comparison with results produced by the corresponding on-line model.

Another approach to meeting the twin demands of high model resolution and computational efficiency is to employ models with dynamically adaptive grids that place added model resolution where it is most needed (*e.g.*, boundary currents, deep-water formation areas, *etc*.).

There is a need for physical models to represent interactions between the open ocean and the coastal zone. Efforts should be undertaken to improve the simulated large-scale physical circulation (*e.g.*, vertical and horizontal mixing, deep water formation), mass exchanges across air-sea, land-ocean, and open ocean-coastal interfaces, and high frequency subgrid-scale and mesoscale variability.

Since one the only tests of changing ocean circulation is the simulation of interannual variability, it will be important that our physical models interannual variability is going to be a critical issue to address.

Model Evaluation and Diagnosis

OCMIP has made a good start at encouraging a new level of model evaluation and diagnosis. This was facilitated by the observational efforts mounted by JGOFS, WOCE, and other programmes. However, it is often very difficult to understand why a global ocean model behaves the way it does. Snapshots, such as WOCE, miss the full dynamic behaviour of the ocean, such that if a model "hits" GEOSECS or WOCE concerning the distributed tracer field and inventories, or returns a "consensus" ocean uptake of anthropogenic carbon it may have done so by an inaccurate pathway. Therefore, a vigorous effort is required to develop the analytical tools needed to diagnose the root cause of the model's failure to adequately simulate observations.

Clearly, such an analytical effort will depend critically on developing an understanding of the key underlying processes.

There is at present no physical ocean model intercomparison project. It may be useful to start such a project, or expand the scope of OCMIP to place greater emphasis on the diagnosis and evaluation of physical ocean transport models. Global model solutions need to be critically assessed against observations, suggesting the need for more comprehensive model-data evaluation standards.

NEED FOR DIVERSITY AND CREATIVITY

We stress here that ocean ecosystems and physics are poorly understood. Given this high state of uncertainty, it is essential that different researchers pursue independent paths, and that we not settle too early on a single biogeochemical modelling framework. To this end, we stress the need for openness and the sharing of model codes, input, and output. Researchers who would like to test the sensitivity of an existing model to a changed parameterization or parameter value should not have to rebuild the model de novo. The ready availability of lower-dimensional physical transport models, especially one-dimensional models configured for each of the time-series stations, would greatly aid the ability of independent researchers and graduate students to contribute to the advancement of the state of the science.

Advances in computational power are allowing eddy-resolving models of the ocean carbon cycle to become a reality. However, insights and advances in prognostic ocean carbon-cycle simulation are likely to come from both high-resolution and coarse-resolution modelling studies. High-resolution modelling promises simulations with greater fidelity; however such modelling efforts can be computationally and monetarily expensive, and even the highest resolution models will not be able to resolve all relevant physical processes. Therefore, new creative methods will be needed to address the impact of subgrid-scale eddies and convection on global-scale ocean biogeochemistry and carbon uptake.

Because of the great expense of such efforts, only several centres internationally can be provided the resources required for high-resolution modelling. However, many researchers and graduate students would have the resources and ability to help analyse the results of such modelling. To maximize benefits from these high-resolution modelling centres, the results, computer codes, and driving data need to be distributed widely in a useable form.

Advances in computational power are allowing coarse-resolution general circulation models to be run on workstations, and further advances in computational technologies could allow such models to be run by many researchers on desktop or laptop computers. To foment this, developed models need to be made readily available to researchers and students who wish to use these models as research tools.

It is essential that we remain open to the possibility that factors that have not been carefully incorporated in models to date (*e.g.*, the role of other micronutrients such as zinc) may be important in structuring ocean ecosystems. At this time, there is not even clear consensus on the degree of model complexity that will be required to adequately simulate the ocean carbon cycle. Models may need to represent detailed ecosystem structure, but highly simplified models may be able to capture the most important aspects of carbon cycling in the oceans.

SUMMARY

Reliable prognostic ocean carbon cycle models are required to predict the evolution of future air-sea CO_2 fluxes and the probable response of these fluxes to changes in CO_2 emissions, climate, and ocean circulation.

Such models critically depend on the existence of observational data and process studies, which contribute to model development, diagnosis, and evaluation. Close collaboration between global-scale prognostic modellers and process studies is essential to (1) determine which process uncertainties most critically affect model predictions, (2) help develop process representations that are suitable for inclusion in global-scale models. Close collaboration between prognostic modellers and observationalists is critical to making sure that the data collected pertain to important process uncertainties and/or really contribute to filling critical data gaps.

Improvements in prognostic ocean carbon-cycle models will likely come from improvements in biogeochemical models (*e.g.*, better representations of multiple nutrient limitation on ecosystem structure, better understanding of remineralisation, *etc*.) and in the underlying physical models (*e.g.*, higher resolution and better representation of unresolved processes). To accelerate progress in ocean carbon cycle simulation, we need to encourage innovation in both biogeochemical and physical modelling. Thus, in addition to several high-resolution modelling centres, we need low-resolution models that are easy to use and readily available to a broad potential research community.

Prognostic ocean carbon-cycle models will play an essential role in coupled climate/carbon-cycle models. Such coupled models will likely be the primary tools for assessing the impact of human activities on the Earth system.

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APPENDICES

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