Prognostic Ocean Carbon-Cycle Modeling

A working document in preparation for an international global carbon-cycle science research plan

prepared by the Prognostic Model Working Group
of the EU/US Ocean Carbon Cycle Science Research Workshop,
Paris, 9-11 Aug 2000; Ken Caldeira, chair

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1. 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. To help make reliable global climate/carbon-cycle predictions, the oceanic research community must provide reliable predictions of the response of the marine carbon cycle to climate change, increasing atmospheric CO_2 content, and human activities. Such a predictive capability depends on the development of models that are based on mechanistic representations of key processes, and carefully evaluated with a diverse set of observations. The primary goals of such modeling 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.

1.1 WHAT IS PROGNOSTIC OCEAN CARBON CYCLE MODELING?

Prognostic ocean carbon-cycle modeling 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 in coupled or off-line modes), or may be provided by assimilation models.

1.2 WHY DO WE NEED PROGNOSTIC OCEAN CARBON-CYCLE MODELING

Prognostic ocean carbon-cycle modeling is needed to:

Predict the impact of anthropogenic carbon emissions on atmospheric CO_2 content

Well-tested prognostic models are needed to predict future air-sea CO_2 fluxes. The oceans are thought to absorb about 1/3 of today's fossil-fuel CO_2 emissions. However, this absorption will become less efficient as the ocean's continue to absorb excess CO_2, and may become less efficient in response to climate-induced changes in ocean mixing and circulation.

Predict the 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 favored 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 outcompeted 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. In a broader view, the change due to acidification of nutrient and carbonate utilization by marine life must be taken into account.

Predict unintentional human impacts on atmospheric CO_2 content and the marine environment

Humans may impact the marine carbon cycle not only by altering climate and atmospheric CO_2 content but also through activities that directly affect ocean biogeochemistry, such as human-induced changes in river fluxes, coastal pollution, and fish stocks. The effect of such activities on marine biota and the ocean carbon cycle are poorly understood, and need to be explored further.

Predict the 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 attempt 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 strategy 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.

1.3 COUPLED CLIMATE AND CARBON SYSTEM MODELING

Coupled climate and carbon system modeling presents a major framework to integrate our understanding of the global system into a predictive 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.

1.4 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 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.

These are a few potential surprises that have been thought of, and there are no doubt other potential surprises about which we do not yet have any foreshadowing. 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. Nevertheless, prognostic models are an essential tool to help prevent our society from being blindsided by a major unanticipated catastrophe.

2. RECENT PROGRESS IN PROGNOSTIC OCEAN CARBON-CYCLE MODELING

Progress in ocean carbon-cycle modeling has come in several areas, including (1) consideration of climate/carbon-cycle interactions, (2) representation of the role of micronutrients in limiting phytoplankton growth, (3) representation of ecosystem dynamics, (4) use of newly available data sets and the development of an institutional framework (OCMIP) to improve model diagnosis and evaluation, and (5) renewed 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, Monfrey, 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 more efficiently utilize nutrients in the surface ocean, which would tend to permit increased oceanic CO_2 absorption. Further advances in prognostic modeling will permit more reliable 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 modeling 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 that feed 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 institutionalize this process. As a result, every major ocean carbon-modeling 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 modeling 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 modeling groups. Further work in this direction will lead to improved predictions of both the effectiveness and environmental impacts of proposed ocean carbon sequestration strategies.

3. LINKS TO OTHER COMPONENTS OF THE PROGRAM

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

3.1 LINKS TO OTHER OCEAN-BASED COMPONENTS

Prognostic ocean carbon-cycle modeling depends on and helps contribute to (i) ocean observational programs, (ii) ocean process studies, and (iii) inverse and assimilation ocean modeling.

3.1.1 LINKS TO OCEAN OBSERVATIONS

Observations of the ocean, and associated observations in the laboratory, obviously forms the foundation of our understanding of oceanic processes and their representation in prognostic models. Furthermore, observations are the sine qua non of model evaluation. The data needs for developing process understanding are discussed elsewhere in this document. Some of the data needs for model evaluation are listed in section 4.3.

Prognostic models can also be used to help determine the best locations to make 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 modelers is 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. Means should be provided for establishing distributed data centers, where observational and model datasets can be accessed easily. Additionally, standard analysis tools should be developed and distributed to encourage such collaboration.

3.1.2 LINKS TO OCEAN PROCESS STUDIES

Reliable prognostic models depend on mechanistically based representations of the underlying critical processes. As such, strong and rapid links to process studies are critical in double way sense.

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 modelers work with mechanistic-process modelers 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 modelers fail to adequately represent the real world will suggest processes that are inadequately represented in the prognostic models. In this way, prognostic modelers can help to determine the set of processes that we need to study most critically to reliably predict future air-sea fluxes.

3.1.3 LINKS TO INVERSE AND ASSIMILATION MODELING

Inverse and assimilation modeling can aid prognostic modeling in several ways. These modeling efforts can provide fields with global distribution that can be used to initialize and evaluate prognostic models. Parameterizations developed for assimilation models can be incorporated, either directly or with modification, into prognostic models.

Similarly, prognostic modelers will be able to provide assimilation modelers with parameterizations of key processes. Areas in which the prognostic modelers 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 modelers 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 both in assimilative or prognostic modes, and that advances in one area will directly contribute to advances in the other. 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.

3.2 LINKS TO OTHER COMPONENTS OF THE CLIMATE/CARBON-CYCLE

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

3.2.1 LAND SURFACE MODELING

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, and through climate. Therefore, a unified model incorporating the land, atmosphere, and ocean components are needed to make reliable predictions.

3.2.2 ATMOSPHERIC INVERSE MODELING

Prognostic modeling can help atmospheric inverse modeling by providing independent boundary conditions for air sea fluxes. Conversely, atmospheric inverse modeling can help ocean modeling 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 occur must be key research areas to be more confident in flux patterns.

3.2.3 ATMOSPHERIC CLIMATE AND CHEMISTRY MODELING

Carbon dioxide is the principal gas of interest to climate modelers. 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.

3.2.4 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 impact human behavior.

The largest human impact on the ocean may be the impact that occurs through global climate change. However, changes in river fluxes associated with water use policy, and land-use practices may significantly affect the oceanic environment. For example, Mississippi River fluxes have been associated with increased hypoxia in the Gulf of Mexico (ref.). More generally, coastal eutrophication may have an increasingly large impact on open ocean environments. Furthermore, overfishing 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 impact human behavior. Increases or decreases in the efficiency of ocean carbon uptake could affect carbon emissions reduction policies. Quantification of oceanic sources and sinks are essential to help evaluate the potential impact of various

4. NEED FOR DIVERSITY AND CREATIVITY

Advances in computational power are allowing eddy-resolving models of the ocean carbon cycle to become a reality. High-resolution modeling promises simulations with greater fidelity; however, such modeling efforts can be computationally and monetarily expensive. Because of the great expense of such efforts, only several centers internationally can be provided the resources required for such modeling. However, many researchers and graduate students would have the resources and ability to help analyze the results of such modeling. To maximize benefits from these high-resolution modeling centers, the results, computer code, and driving data associated with high-resolution simulations need to be distributed as widely as possible in a form that is easily digestible by the research community.

Insights and advances in prognostic ocean carbon-cycle simulation are likely to come from both high-resolution and coarse-resolution modeling studies. 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. 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. However, developed models need to be made readily available to researchers and students who wish to use these models as research tools.

5. RESEARCH FOCUS

The current generation of ocean biogeochemical models contain 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 modeling are needed to address these issues (see Table X).

5.1 BIOGEOCHEMICAL MODEL DEVELOPMENT

Biogeochemical models are critical to determining air-sea fluxes of CO_2. In large part this is 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.

5.1.1 OCEAN ECOSYTEM 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, and often talk of the need to represent various genera or species in an effort to get at these underlying processes. The motivation for representing this level of detail is similar to the motivation for representing various ecosystem types in land surface 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.

5.1.2 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 reduce 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.

5.1.3 THE ROLE OF PARTICULATE MATTER

Particulate organic matter (POM) 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 POM tends to drive a flux of CO_2 into the ocean where it is generated; however, when the parcel of water into which the POM remineralizes (i.e., oxidizes) 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 blooms) 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 remineralize in the upper ocean, where it the carbon may be retained for months to decades.

The factors that control the production and remineralization of organic matter are poorly understood. In particular, there is extremely little mechanistic understanding of the processes that control the remineralization 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 remineralization. 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., modeling the ecosystems of the ocean interior).

5.1.4 THE ROLE OF DISSOLVED ORGANIC MATTER

Dissolved organic matter (DOM) is generated by ecosystems in the euphotic zone (the zone in the upper ocean that receives adequate sunlight to support photosynthesis). Some of this organic matter is mixed or advected downward into the upper thermocline (50 m - 500 m depth), where it remineralizes (i.e., oxidizes) 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.)

Longer lasting DOM transports carbon and nutrients further from the euphotic zone. This would tend both to store carbon deeper in the ocean interior, and move nutrients away from where they can support photosynthesis in the upper ocean. DOM appears to be a heterogeneous mixture of material, ranging from labile organic material that remineralizes 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.

5.1.5 THE NEED FOR CREATIVITY AND NEW IDEAS

We stress here that marine ecosystems are poorly understood. Therefore, 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 it is also possible that highly simplified models may be able to capture the most important aspects of carbon cycling in the oceans.

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 modeling 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 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.

5.2 PHYSICS AND TRANSPORT MODEL DEVELOPMENT

Current prognostic ocean circulation models used to study the carbon cycle study also 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, although state-of-the-art global physical models are available that resolve some eddies, due to their computational costs, such models cannot be used for the millenial scale simulations required to conduct global ocean carbon cycle simulations.

This constraint could be overcome through the use of highly-efficient off-line tracer transport models. Prognostic biogeochemical model could then be used with 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.

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.

5.3 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 programs. However, it is often very difficult to understand why a global ocean model behaves the way it does. Therefore, there needs to be a vigorous effort 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.

5.4 COUPLING WITH OCEAN-LAND-ATMOSPHERE-ICE CLIMATE/CARBON-CYCLE MODELS

The two major issues facing researchers studying the carbon cycle is (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 can 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 modeling is to provide the oceanic component of coupled ocean/atmosphere/land-surface/sea-ice climate and carbon-cycle models.

6. 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 modelers 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 modelers and observationalists is critical to making sure that the data collected pertains to important process uncertainties and/or really contributes 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 remineralization, 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 modeling. Thus, in addition to several high-resolution modeling centers, 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 tool for assessing the impact of human activities on the Earth system.