Evaluation and Intercomparison of Three-Dimensional Global Marine Carbon Cycle Models

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1. Introduction

1.1. *The need for marine carbon cycle models*

The addition of carbon dioxide to the atmosphere from fossil fuel burning and deforestation has profound implications for the future of the earth's climate and hence for humankind itself. Society is looking toward the community of environmental scientists to predict the consequences of increased atmospheric carbon dioxide so that sound input can be provided to economists, environmental engineers, and, ultimately, policy makers. Environmental scientists have responded to this challenge through the creation of several ambitious, highly-coordinated programs, each focussed on a different aspect of the climate system. Recognizing that numerical models, be they relatively simple statistical-empirical models or highly complex process-oriented models, are the *only* means for predicting the future of the climate system, all of these programs include the development of accurate, predictive models as a central goal. The Joint Global Ocean Flux Study (JGOFS) is one such program, and was built on the well-founded premise that biological, chemical and physical oceanographic processes have a profound influence on the CO₂ content of the atmosphere. The cap-stone phase of JGOFS, the Synthesis and Modeling Project (SMP), is charged with the development of models that can be used in the prediction of future air-sea partitioning of CO₂.

JGOFS, particularly the SMP phase, has a number of interim goals as well, including the determination of fluxes and inventories of carbon in the modern ocean that are germane to the air-sea partitioning of CO₂. Models have a role to play here too, because many of these fluxes and inventories—such as the distributions of anthropogenic dissolved inorganic carbon (DIC), new primary production and aphotic zone remineralization—while not amenable to direct observation on the large scale, can be determined using a variety of modeling approaches (Siegenthaler and Oeschger, 1987; Maier-Reimer and Hasselman, 1987, Bacastow and Maier-Reimer, 1990; Sarmiento *et al.*, 1992, Najjar *et al.*, 1992).

These twin needs for the development of marine carbon cycle models are expressed in two of the main elements of JGOFS SMP. (1) extrapolation and prediction, and (2) global and regional balances of carbon and related biologically-active substances. We propose to address these program elements through a coordinated, multi-investigator project to *evaluate* and *intercompare* several 3-D global marine carbon cycle models.

1.2. *Why evaluate models?*

The evaluation of marine carbon cycle models that address the SMP elements is necessary for two reasons. First, evaluation is needed to determine the reliability of predictions and the estimates made by the models. Second, and more importantly, evaluation leads to the identification of model weaknesses and strengths, and directs efforts towards model improvement. The data collected by the JGOFS field programs have created a superb opportunity for model evaluation, an example of which is shown in Figure 1 from work by two of us (Sabine and Sarmiento). This figure shows a comparison of anthropogenic marine dissolved inorganic carbon estimated from observations with a simulation using the Princeton University/Geophysical Fluid Dynamics Labo-

Fig 1 (a) Marine anthropogenic DIC in the Eastern Indian Ocean (along 95°E) in 1995 computed using measurements from the JGOFS CO₂ survey and the method of Gruber *et al* (1996). This method employs a new quasi-conservative tracer, C*, which is defined as the difference between the measured DIC concentration of a water parcel, corrected for biology, and the concentration the water parcel would have at the surface in equilibrium with a preindustrial atmosphere. C* reflects both the anthropogenic signal and the air-sea disequilibrium component. The air-sea disequilibrium component can then be discriminated from the anthropogenic signal using either information about the water age (e.g., from transient tracers such as CFCs or ³H-³He) or the distribution of C* in regions not affected by the anthropogenic transient. (b) A section of anthropogenic DIC estimated from the Princeton ocean carbon cycle model for the same year in the grid boxes covering the longitude range of the cruises. Each point in (a) represents a computed value. Dashed lines in (b) indicate the midpoints of the vertical grid boxes of the model.

ratory (GFDL) global ocean model in the Eastern Indian Ocean. The observed field is based on measurements made as part of the JGOFS CO₂ survey and the method of Gruber *et al* (1996) for determining the anthropogenic component of the dissolved inorganic carbon (DIC) distribution (see caption). Although some of the overall structure of the observations is captured in the model, the penetration of anthropogenic CO₂ in the model is too weak in low latitudes and too strong in high latitudes of the Southern Ocean. Such an evaluation not only allows error bars to be put on the model prediction, but is now focussing efforts on identifying and improving those aspects of the model, chiefly its circulation field, that are responsible for the discrepancies.

A second example, shown in Figure 2, illustrates the potential of satellite observations for evaluating models of the natural carbon cycle. This figure is a comparison of the surface chlorophyll distribution estimated from satellite (the Coastal Zone Color Scanner, CZCS) with that simulated by the ecosystem model of Doney *et al* (1996) embedded in the three-dimensional ocean model used for the Climate System Model (CSM) of the National Center for Atmospheric Research (NCAR). The main features of the CZCS data are captured by the model surface chlorophyll field, including the bloom in the high latitude North Atlantic, locations of the subpolar/subtropical chlorophyll transition zone, and the low to moderate chlorophyll concentrations in the Antarctic Circumpolar region. Similar model skill is found for the annual cycle (not shown), for example in simulating the expansion of the subtropical oligotrophic regions in the summer hemisphere and the weak seasonal cycle in the Southern Ocean. The original model version based strictly on Doney *et al* (1996) had difficulty capturing simultaneously the spring bloom in the

Fig. 2. (a) Modeled and (b) observed distributions of surface chlorophyll for climatological July. The simulation is based on the five-compartment ecosystem model of Doney *et al.* (1996), with additional modifications, particularly iron limitation (see Section 4.2). Observations are based on a composite of satellite ocean color measurements from the Coastal Zone Color Scanner (CZCS).

North Atlantic and the low chlorophyll in the Southern Ocean. Modifications to reduce the southern ocean biomass (e.g. reduced growth rates, increased grazing rates or phytoplankton mortality) tended to also damp the Northern Hemisphere signal. This problem was partially alleviated by adding an iron limitation term to the phytoplankton growth equation based on the global mineral aerosol deposition maps of Tegen and Fung (1994). With the great advances in quantity and quality of ocean color data expected from SeaWiFS and other satellites, model evaluations such as this will be even more fruitful, leading to rapid developments in marine carbon cycle models.

Historical data sets also show promise for extensive model evaluation. Until recently, most global climatological data sets did not resolve the important annual cycle for many important marine biogeochemical quantities (Berger *et al.*, 1987, Levitus, 1982, Levitus *et al.*, 1993, Conkright *et al.*, 1994). Now there exist seasonal climatologies for surface $p\text{CO}_2$ (Takahashi *et al.*, 1997), oxygen (Levitus and Boyer, 1994, Najjar and Keeling, 1997) and nutrients (Conkright *et al.*, 1996), all of which will greatly extend the capability for model evaluation.

Thus, as a result of the current emergence of the JGOFS, satellite and historical data sets, the timing is perfect for an aggressive and unprecedented program of model evaluation. As the above examples suggest, this evaluation promises not only to place more reliable error estimates on model predictions, but also to identify key weaknesses of marine carbon cycle models, which will then stimulate model improvement.

1.3. Why intercompare models?

Normally, models are improved by individual modeling groups in isolation. The typical model development process is iterative, consisting of model evaluation using observations, model reformulation, simulation, and re-evaluation (Figure 3). This process is time-consuming and expensive for global 3-D marine carbon cycle models. Model intercomparison, if carefully coordinated, can accelerate model improvement because different models are bound to perform with varying degrees of success, and the identification of the causes of model strengths and weaknesses will be facilitated, leading to a more rational model adjustment. A second role of intercomparison is the improvement of model error estimates. The range of estimates provided by a variety of viable models provides an uncertainty that is difficult to obtain from an individual model, particularly

Fig 3 A schematic diagram showing the intervention of model intercomparison (shaded circle) in the normal model development process (unshaded boxes) undertaken by individual investigators

Fig 4 The zonally integrated air-to-sea flux of anthropogenic CO_2 averaged for the 1980s as simulated by four 3-D marine carbon cycle models: Princeton/GFDL, The Hadley Center, The Max-Planck Institute für Meteorologie (MPI) and the Institute Pierre Simon LaPlace (IPSL)

if the model can not be directly evaluated, such as in the case for future predictions

Does the model intercomparison methodology work? One must answer yes, based on the fruitful results of intercomparisons of climate models (Gates, 1992; Cess *et al*, 1995; Santer *et al*, 1996), atmospheric CO₂ transport models (Law *et al*, 1996) and land-surface models (Henderson-Sellers *et al*, 1993, Henderson-Sellers *et al*, 1996), in addition to preliminary results from the initial phase of the Ocean Carbon-cycle Model Intercomparison Project (OCMIP), initiated in 1995 by the Global Analysis, Interpretation and Modeling (GAIM) Task Force of the International Geosphere-Biosphere Program (IGBP). OCMIP has revealed that the 1980s global ocean uptake by the four participating models differs by only $\pm 20\%$ (1.5 to 2.2 Gt C yr⁻¹), but regionally the models differ greatly, particularly in the Southern Ocean (south of 30°S) where the quantity absorbed differs by nearly a factor of two (Figure 4). This region also dominates the global uptake in the models. All of the models estimate that from one-half to one-third of the total uptake is in this region. With time, as the Southern Ocean sink becomes larger relative to other regions, differences among the models in their total uptake will grow considerably, representing a significant uncertainty in the ability to predict future levels of atmospheric CO₂. These results are now provoking the careful evaluation of the models with relevant observations (such as anthropogenic CO₂, chlorofluorocarbons, and radiocarbon) and the identification of the processes that cause such differences among the models (Orr *et al*, 1997, Sarmiento *et al*, 1997). Because the only difference among the models is the circulation field (identical gas exchange parameterizations and carbonate chemical equilibrium constants were agreed upon beforehand), this intercomparison highlights the important differences in Southern Ocean circulation with regard to anthropogenic CO₂ uptake. This example shows that carefully designed simulations in a coordinated intercomparison project can lead to increased understanding and focus model development.

1.4. The next phase of OCMIP

We are seeking support for scientists at five U.S. institutions (four of which will be running models) to go beyond the early exploratory phase of OCMIP, which involved only four institutions making only a few specific simulations: anthropogenic CO₂ uptake (1765-present), bomb radiocarbon uptake and the ocean's solubility pump. Here we propose to

- (1) add three more modeling groups to OCMIP—National Center for Atmospheric Research (NCAR), Lawrence Livermore National Laboratories (LLNL), and Massachusetts Institute of Technology (MIT)
- (2) extend the series of simulations to include biological processes, chlorofluorocarbons, natural radiocarbon, and future atmospheric CO₂ stabilization scenarios
- (3) facilitate model evaluation by directly involving observationalists and data synthesists.

A three-year collaborative proposal by seven European modeling groups to conduct a related series of model evaluations and intercomparisons has recently been approved by the European Commission. We have been in close contact with the European groups, led by James Orr of the Institut Pierre Simon Laplace (IPSL), and will coordinate with ~~the~~ them (see Section I) so that there is the potential of 11 models participating in an international project to evaluate and intercompare global marine carbon cycle models. Our involvement with this international project will ensure that the United States continues to play a leading role in the development of global marine carbon cycle models.

For a model intercomparison to be most fruitful, several significantly different, but equally viable models must participate. How different are the models we propose to use? The details of the physical and biogeochemical models we bring to this study are discussed in detail in Section 4, but here we present estimates of export production simulated in three of these models, though each in an early phase of their development (Figure 5). It is clear that the three models give quite different meridional distributions of export. The simplicity of the MIT export parameterization gives rise to some of this difference; for example, the all round weaker export is due to the specified long lifetime of nutrients in surface waters. The other two models, which are in many ways very similar, still display considerable differences that may be attributable to the parameterizations of sub-grid scale mixing. The fact that these models reveal significant differences in a key process of the marine carbon cycle (export production) suggests that a detailed intercomparison of the models will be fruitful.

1.5. Focus on the Southern Ocean

Most of the evidence points to the Southern Ocean as a key player in the ocean-atmosphere partitioning of CO_2 , both in the natural carbon cycle and its anthropogenic perturbation. In both cases, the Southern Ocean exerts considerable influence on atmospheric CO_2 because its surface waters have a great areal extent and are in intimate contact with the large volume of the deep ocean through upwelling and convection. Also, the abundance of surface nutrients in the Southern Ocean means that biological processes have the potential to dramatically modify the surface carbon balance in this region (Sarmiento and Toggweiler, 1984; Knox and McElroy, 1984; Siegenthaler *et al.*, 1984; Sarmiento and Orr, 1992). Future scenarios of the air-sea partitioning of CO_2 further emphasize the likely importance of the Southern Ocean. A simple carbon cycle embedded in the Manabe and Stouffer (1993) ocean model—which exhibited a collapse of the thermohaline circulation in response to enhanced atmospheric CO_2 —suggests that marine biogeochemical feedbacks on atmospheric CO_2 are significant and complex, with the locus of this feedback in the Southern Ocean (Sarmiento and LeQuéré, 1996).

Despite its importance to the marine carbon cycle, the Southern Ocean is probably the least understood open ocean region, both in terms of its physical and biogeochemical characteristics. This is the region of the ocean where the uptake of anthropogenic CO_2 is most variable in

Fig. 5 Annual- and zonal-mean export production from (earlier versions) of three of the models that will take part in the proposed study. The LLNL and Princeton models restore surface phosphate to observations and the MIT model has a fixed lifetime for surface nitrate. Productivity has been converted to carbon units assuming a P:N:C Redfield ratio of 1:16:130. The models also differ in spatial and temporal resolution, representation of remineralization at depth, and in physical parameterizations, including sub-gridscale mixing.

prior model simulations, mainly due to differences in the circulation field and mixing parameterizations (Figure 4). Great challenges exist for the ocean models in this region, including the parameterization of sub-gridscale eddy mixing (Danabasoglu and McWilliams, 1995; England, 1995) and the biogeochemical dynamics of High-Nutrient Low-Chlorophyll (HNLC) regions (Chisolm and Morel, 1991). We will make the Southern Ocean a particular focus of our model evaluation and intercomparison activities. Further, we believe that the additional data sets that we will bring to our model evaluation and intercomparison will identify other regions or processes of key importance to the marine carbon cycle and the air-sea partitioning of CO₂.

2. Objectives

The long-term objectives of this project are

- (1) To improve 3-D marine carbon cycle models for their use in predicting the future partitioning of carbon dioxide between the atmosphere and the ocean**
- (2) To provide regional and global estimates and uncertainties of important but poorly-known quantities that are relevant to the marine carbon cycle: new production, aphotic zone remineralization and anthropogenic CO₂ fluxes and inventories**

Since the above objectives require an understanding of the natural marine carbon cycle and its anthropogenic perturbation, both of which are profoundly influenced by ocean circulation, we propose the following three shorter-term objectives

- (1) To evaluate and intercompare the ability of four 3-D global models to simulate the natural marine carbon cycle**
- (2) To evaluate and intercompare the ability of four 3-D global models to simulate the marine uptake of anthropogenic CO₂**
- (3) To evaluate and intercompare those aspects of the circulation fields of the four models that are relevant to the natural marine carbon cycle and its anthropogenic perturbation**

To achieve these objectives we propose a series of simulations (Table 1), all of which, except for the future scenarios, are designed so that they may be readily evaluated with observational data sets. In some cases, these data sets already exist, while in other cases significant work will be required to put data in a format suitable for the processes of model evaluation and intercomparison. Therefore, we are requesting support for (1) creating syntheses of observations, (2) performing simulations, and (3) evaluating and intercomparing the results of the simulations.

3. Work plan

In this section we describe in more detail the experiments to be performed (listed in Table

1) and how we will compare and evaluate the model results.

Table 1: Set of proposed simulations.

1. Natural marine carbon cycle Solubility pump only (DIC only) Biological plus solubility pump (PO ₄ , O ₂ , DIC and Alk) Nutrient-restoring model Individual investigator model
2. Anthropogenic carbon in the oceans 1765-present IPCC scenarios S450 and S650
3. Tracers of ocean circulation Natural and bomb radiocarbon Chlorofluorocarbons 11 and 12

3.1. The natural marine carbon cycle

The natural marine carbon cycle (which we take to mean its preindustrial state) plays an important role in the partitioning of CO₂ between the atmosphere and the ocean through two important processes, the solubility pump and the biological pump (Volk and Hoffert, 1985). Both of these processes act to create a global mean increase of DIC with depth, and therefore to maintain atmospheric CO₂ at a level considerably lower than it would otherwise be (Sarmiento and Toggweiler, 1984; Volk and Hoffert, 1985; Najjar, 1992). The solubility pump maintains a vertical DIC gradient due to the fact that cold surface water, which originates in high latitudes and fills up the deep ocean, can hold more DIC than warm water at equilibrium with a fixed atmospheric pCO₂. The biological pump consists of two separate pumps: that of organic matter and calcium carbonate. The organic matter pump affects the DIC distribution through the photosynthetic formation of organic carbon in surface waters and the sinking and subsequent remineralization of this organic matter deeper in the water column. The carbonate pump affects the DIC distribution through the biogenic precipitation of calcium carbonate in surface waters and the subsequent sinking and dissolution of this material deeper in the water column. The two biological pumps also affect the alkalinity of seawater through the nitrate and dissolved calcium distributions.

3.1.1 Solubility pump

Simulations. Ocean carbon cycle models provide an attractive, simple method of estimating the solubility pump by specifying atmospheric CO₂ and determining the oceanic DIC distribution that results from air-sea gas transfer of CO₂ and its inorganic chemistry in seawater. We will use this approach to simulate the solubility pump in the four ocean models. Ocean advection and mixing are perhaps the most important, but least constrained aspect of the solubility pump. We will perform these simulations in such a way as to elucidate the impact (as yet uncharacterized and unquantified) of the different model circulations and mixing parameterizations on the strength of the solubility pump. The range of model circulations will provide a spread, and a feel for some potential errors, in the computed estimate of the solubility pump. Such an error estimate would be difficult to make with a single model alone.

The remaining parameterizations and specifications—such as those for preindustrial atmospheric CO₂ content, the air-sea gas transfer velocity, the equilibrium constants for the carbonate system, the sea surface alkalinity distribution, surface wind speed, sea surface temperature, sea surface salinity, sea ice fraction and air-sea fresh water fluxes (which affect the DIC distribution)—will follow OCMIP protocols¹ so that comparison with other modeling groups (such as the Europeans) will be straightforward

Evaluation The model simulations of the solubility pump will be compared to the observed DIC distribution, with the anthropogenic component removed (Gruber *et al.*, 1996), to determine the relative strengths of the solubility and biological pumps. One of us (Sabine) will be applying the Gruber *et al.* technique to the JGOFS CO₂ survey data and making the results available for model evaluation.

3.1.2. The organic matter pump

If C, N and P in organic matter are cycled in relatively fixed proportions on a global scale (Redfield *et al.*, 1963, Takahashi *et al.*, 1985; Anderson and Sarmiento, 1995) then simulation of the organic matter pump is tantamount to simulating the distributions of nitrate or phosphate. Clearly there are deviations from an invariant “Redfield stoichiometry” (Sambrotto *et al.*, 1993, Emerson and Hayward, 1995, Michaels *et al.*, 1994), but we will, at least initially, regard these deviations as relatively minor. Even with this simplification, however, simulating the ocean’s organic matter pump is made difficult by the variety of processes that govern the formation of organic matter in the euphotic zone, its export to depth and its subsequent remineralization. Unlike ocean circulation, no fundamental set of equations that govern nutrient cycling has been found. Thus a wide range of biological models of varying sophistication have been put forward for specific problems (e.g., Najjar *et al.*, 1992; Sarmiento *et al.*, 1993, Six and Maier-Reimer, 1996), and model development is proceeding rapidly (Evans and Garçon, 1997). Based on these considerations, we propose a two-tiered approach to simulating the organic matter pump

1. An idealized “nutrient restoration” parameterization, which all of the modeling groups will adopt. Although non-mechanistic, this simple approach has the advantages of being constrained by observations and allows a straightforward intercomparison of the effect of the different models’ physical nutrient supply on new production.
2. Process-oriented nutrient cycle models, which will differ among the modeling groups. This approach encourages the modeling groups to explore a diversity of mechanistic approaches for simulating the complex processes that regulate new production.

Nutrient restoring simulations. In this approach, the observed, monthly mean distribution of surface phosphate will be imposed on the model. Thus, when a model’s ocean circulation brings phosphate-rich water to euphotic zone (taken to be the upper 100 m), enough nutrients are removed to bring surface waters in agreement with observations. In practice, this will be done by restoring nutrients to observations on a 30-day time scale (Najjar *et al.*, 1992). The removal of nutrients in surface waters represents new production of organic matter whose fate will be mod-

¹ Information about OCMIP, including simulation protocols can be found on the OCMIP home page <http://pyramid.unh.edu/csrc/gaim/ocean.html>

Fig 6 New production simulated by the Lawrence Livermore National Laboratory global ocean model using the nutrient restoring technique. The model was restored to a harmonic fit of a preliminary version of the four-season phosphate climatology discussed by Conkright *et al.* (1996). Restoring was performed on a time scale of 30 days throughout the upper 50 m. A C:P ratio of 106 was used, with 20% of export production being transferred to DOM that has a lifetime of 25 yr. The remaining 80% is transferred to particulate matter, which is remineralized instantly below 100 m following the sediment trap-based flux formulation of Suess (1980).

Fig 7 Seasonal variation of the average oxygen anomaly (the departure from saturation) at selected depths between 30°N and 42°N in the Pacific Ocean. Symbols are the actual averages and curves are annual harmonic fits. The cycles at 0 and 30 m reflect summertime new production and warming, and wintertime entrainment of deeper oxygen-depleted water. The increased amplitude and advanced phase at 30 m are consistent with photosynthetic oxygen trapped in the seasonal thermocline. At 125 m and 200 m, the oxygen anomaly decreases during the summer due to respiration and increases during the winter due to ventilation. From Najjar and Keeling (1997).

eled following Anderson and Sarmiento (1995). New production is split evenly between particulate organic matter (POM) and as dissolved organic matter (DOM). POM is assumed to be remineralized immediately below 100 m according to the length scale given by the organic carbon sediment trap observations of Martin *et al.* (1987). DOM is advected and diffused into the thermocline and remineralized with a time constant of 10 years.

Soon-to-be-released global syntheses of surface nutrients by the National Oceanographic Data Center (NODC) (Conkright *et al.*, 1996) allow the nutrient-restoring approach to be adopted on a seasonal timescale, previously this approach was limited to annual mean models (Najjar *et al.*, 1992) due to the lack of seasonally-resolved surface nutrient observations. One of us (Caldeira) has acquired a preliminary version of the NODC synthesis and adopted the nutrient-restoring approach to simulate new production (Figure 6). Results appear very reasonable, with high new production in the upwelling zones along the equator and in high latitudes during the summer and low new production in the downwelling regions and in high latitudes during winter.

Evaluation Recent global syntheses of dissolved oxygen observations in the upper ocean reveal the processes of new production and aphotic zone remineralization (Levitus and Boyer,

1994, Najjar and Keeling, 1997, Figure 7) on a seasonal time scale, thereby providing a crucial observational target for global marine carbon cycle models. We will therefore include oxygen in all of our simulations of the biological pump, linking the O_2 source/sink distribution to that of phosphate using a fixed $O_2:P$ Redfield ratio of 170 (Anderson and Sarmiento, 1994). Gas exchange of oxygen will be treated identically to that for CO_2 , except for the difference in Schmidt number between the two gases (Wanninkhof, 1992). The simulations will be evaluated using the seasonal oxygen climatologies. Though data coverage is a concern with these climatologies, recent work by Keeling *et al.* (1997) shows a high degree of consistency between the Najjar and Keeling (1997) dissolved oxygen climatology and seasonal variations in atmospheric O_2/N_2 , suggesting that seasonal O_2 variations have been adequately resolved in the ocean.

The advantage of the nutrient-restoring approach is that it provides a data-constrained, but model-facilitated estimate of an important but poorly constrained quantity on large scales: new production. Given that the new production so estimated will depend critically on the model ocean circulation field, the variety of estimates from the different circulation models used in this study will produce confidence intervals for predicted global and regional new production. Further, these simulations should provide estimates of how the models differ in their nutrient supply rates, information that will be crucial for interpreting the process-oriented models that each group will employ. Ecosystem modeling studies show that this physical supply is often the cause for model error (Sarmiento *et al.*, 1993, Fasham *et al.*, 1993). A second advantage of this approach is that it facilitates a focus on aphotic zone remineralization. Modeling studies suggest that the aphotic zone nutrient and oxygen distributions are highly sensitive to the type of organic matter (dissolved or sinking particulate) exported from the euphotic zone, as well as the lifetime of that organic matter (Bacastow and Maier-Reimer, 1990, Najjar *et al.*, 1992, Yamanka and Tajika, 1996). Thus, improved estimates of aphotic zone remineralization can be achieved by evaluating models with aphotic zone nutrient and oxygen distributions. The nutrient-restoring models will therefore be run until most of the water column comes into equilibrium (several thousand years).

Process-oriented simulations. The main disadvantage of the nutrient restoring approach is that it is of little use for predicting future variations in the natural marine carbon cycle, such as might be expected if ocean circulation changes, since we do not expect surface nutrient fields to be unchanging. To address this problem, we are proposing that each of the four modeling groups explore their choice of biological model beyond the nutrient restoring model. The approaches taken are purposely diverse so that the trade-offs between simplicity and fidelity can be evaluated. The NCAR approach will be the ecosystem approach, using a four-compartment (nutrient, phytoplankton, zooplankton, detritus) model. The Princeton model will adopt a process-based model with only two state variables: phytoplankton and remineralization/export. The MIT model will adopt a parameterization in which new production is simply a function of surface nutrient concentration and solar irradiance. Finally, the LLNL model will base the simulation of new production on satellite primary productivity and a relationship between the ratio of new production to primary production (the *f*-ratio) and nutrient concentration. Further details of the biological models are given in Section 4.

Evaluation. The focus of the process-oriented modeling efforts will be the simulation of the seasonal climatological nutrient (Conkright *et al.*, 1996) and dissolved oxygen anomaly (Levitus and Boyer, 1994, Najjar and Keeling, 1997) fields in the upper ocean, because these are the most extensive observational data sets that reflect the efficiency of the organic matter pump and

new production (Therefore, we will include oxygen in the process-oriented models by linking it to nutrients as in the nutrient-restoring models) Additionally, satellite-based estimates of surface chlorophyll and primary production from SeaWiFS will be used to evaluate the Princeton and NCAR models The JGOFS process studies and time-series measurements of chlorophyll, primary production, new production, particle fluxes, nutrients and oxygen will also be indispensable for model evaluation on local scales Because the process-oriented simulations will be focused on the upper ocean, we expect them to be relatively short (several decades), since surface waters will come to equilibrium fairly rapidly To prevent the deep ocean nutrient and oxygen concentrations from drifting, these will be restored to the annual mean observations of Conkright *et al* (1994) and Levitus and Boyer (1994) below 1000 m, which, in most regions, is below the depth of seasonal influences

3.1.3 The calcium carbonate pump

Simulating the calcium carbonate pump with a process-oriented model presents another level of complexity beyond simulating the organic matter pump the distribution of particular phytoplankton species (mainly coccolithophorids) must be simulated Further, the dynamics of CaCO_3 dissolution are very complex, depending largely on sedimentary processes Finally, it is difficult to evaluate models of the CaCO_3 pump because the alkalinity distribution is ~~the~~ essentially the only data set that can be brought to bear on the problem, and this distribution is dominated by the fluxes of fresh water across the air-sea interface.

Based on these considerations, we plan to follow the method of Murnane *et al.* (1997), in which the observed nitrate- and salinity-corrected alkalinity (A) is used to constrain the carbonate pump Upper ocean changes in A are distributed according to new production, and at depth dissolution is performed in such a way to ensure that the global mean profile of A remains in agreement with observations Murnane *et al* (1997) find this simplified approach reproduces interbasin differences in deep ocean alkalinity and carbonate ion saturation horizon

3.1.4 The combined pumps

Simulations The natural DIC distribution will be simulated by combining the three carbon pumps. Boundary conditions and carbonate system parameters will be identical to those used in the solubility pump simulations The effects of the organic matter and calcium carbonate pumps on DIC will be simulated by linking the source/sink distribution of DIC to that for phosphate and CaCO_3 , using Redfield ratios of 140 (Anderson and Sarmiento, 1994) and -1, respectively The effects of the organic matter and calcium carbonate pumps on alkalinity will be simulated by linking the source/sink distributions of alkalinity to that for phosphate and CaCO_3 , using Redfield ratios of 16 (Anderson and Sarmiento, 1994) and -2, respectively

Evaluation The models will be evaluated using DIC (with the anthropogenic signal removed) and alkalinity distributions from the JGOFS CO_2 survey as well as historical data (e.g., from GEOSECS) The global, seasonal air-sea $p\text{CO}_2$ difference ($\Delta p\text{CO}_2$) analyses of Takahashi *et al.* (1997) will also be used to evaluate the models, though only the seasonally-varying component, since there have been long term changes in the surface $\Delta p\text{CO}_2$ due to the anthropogenic increase in atmospheric $p\text{CO}_2$

3.2. Anthropogenic carbon in the oceans

In order to simulate the marine uptake of anthropogenic CO₂, we employ the “perturbation method,” which, by assuming the absence of marine biogeochemical feedbacks and ocean circulation changes, can determine uptake simply by specifying the time history of atmospheric CO₂, the gas transfer velocity, the initial state of the carbonate system in surface waters, and ocean circulation (Siegenthaler and Oeschger, 1987). We are well aware that biogeochemical processes are, in reality, important for setting the initial conditions, and that there is the potential for complex marine biogeochemical feedbacks on atmospheric CO₂, particularly if ocean circulation changes (Sarmiento and LeQuéré, 1996). However, we believe it is premature to explore all the biogeochemical feedbacks in the context of this intercomparison project.

Ocean circulation plays the most important, but most poorly quantified role in the uptake of anthropogenic CO₂. Thus, the emphasis of anthropogenic CO₂ simulations will be to simulate uptake with different circulation models but identical initial conditions, atmospheric boundary conditions, gas exchange parameterizations, surface alkalinity and chemical equilibrium constants. The latter three will be identical to those used in the solubility pump simulations. We propose to conduct one simulation spanning preindustrial times to the present, and two simulations of future ocean uptake based on atmospheric CO₂ stabilization scenarios (Table 1).

3.2.1. 1765-present

Simulations. To simulate past and present ocean uptake of anthropogenic CO₂, the four models will be run from 1765 to the present, forced with the corresponding history of atmospheric pCO₂, as determined from ice core records and direct measurements (Enting *et al.*, 1994). The initial surface ocean pCO₂ will be specified from the “best” model simulation of the natural carbon cycle (with all of the carbon pumps) in surface waters, based on an evaluation using surface nutrients, dissolved oxygen and the seasonal variations of surface pCO₂.

Evaluation. The simulations of past and present uptake of anthropogenic CO₂ will be evaluated mainly with data-based estimates of marine anthropogenic DIC (Gruber *et al.*, 1996, Sabine *et al.*, 1997, see also Figure 1) for the early 1990s (mainly from the JGOFS CO₂ survey data) as well as from the 1970s and 1980s (e.g., GEOSECS).

3.2.2. Future stabilization scenarios

The Intergovernmental Panel on Climate Change (IPCC) has proposed several atmospheric CO₂ scenarios as potential targets for the stabilization of atmospheric CO₂ over the next few hundred years. We will force our models with two of these stabilization scenarios over the next 300 years. The models will predict the marine uptake of anthropogenic CO₂ necessary to be consistent with these scenarios, and will provide estimates of what the fossil fuel plus terrestrial CO₂ inputs must be to achieve these targets. The range of uptake predicted by the models is essentially an estimate of the error, which would be difficult to estimate from one model alone. In the first scenario (S450), atmospheric pCO₂ increases monotonically from its present value to a constant value of 450 μ atm by about the year 2075. The second scenario (S650) is similar, except that a constant value of 650 μ atm is reached by about the year 2200. Both simulations will be run until the year 2300. These models will be initialized with output from their own simulations anthropo-

genic CO₂ from 1765 to the present

3.3. Tracers of ocean circulation

Recognizing that ocean circulation plays a key role in the natural and anthropogenic marine carbon cycle, we propose to conduct several simulations of tracers that satisfy two criteria (1) the tracers provide information about the types of ocean circulation relevant for the marine carbon cycle and (2) they have been extensively measured in the ocean. Radiocarbon, both natural and bomb-produced, and chlorofluorocarbons (CFCs) satisfy both of these criteria. The transient tracers (bomb ¹⁴C and CFCs) are particularly attractive because they have atmospheric histories similar (though not identical) to anthropogenic CO₂ and they have equilibration times in surface waters (~1 month for CFCs and 10 years for ¹⁴C) that bracket the equilibration time for CO₂ (~1 year). Natural radiocarbon is most useful for establishing a model's veracity of the circulation of abyssal waters, which currently do not play a large role in CO₂ uptake, but will likely become very important over the next few hundred years. The availability of ¹⁴C and CFC data is rapidly increasing as a result of measurements made as a part of the World Ocean Circulation Experiment (WOCE). One of us (Key) is a WOCE investigator working with the radiocarbon data, and will (1) make these data accessible to our project in a format suitable to facilitate model evaluation, (2) aid in the evaluation of the model circulation fields using the radiocarbon data. In a similar manner, John Bullister (Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration) will collaborate with us on using the CFCs for model evaluation (see Section I).

3.3.1 Natural radiocarbon

We will simulate the natural radiocarbon distribution in our four models following OCMIP guidelines, which generally adopt the approach of Toggweiler *et al.* (1989a). Atmospheric Δ¹⁴C (the fractionation-corrected permil departure from a standard ¹⁴C/¹²C ratio) is set to 0 permil and gas exchange is parameterized using the same formulation as for CO₂. In the model, a simplification is made by assuming that the ¹⁴C/¹²C ratio is conservative with respect to mixing (Fiadiero, 1982, Toggweiler *et al.*, 1989a). These simulations will be run until the deep ocean comes into equilibrium, which typically takes several thousand years. Natural radiocarbon is used most effectively as a diagnostic of deep ocean circulation because of the limited number of observations made before the influence of nuclear bomb tests on the radiocarbon distribution.

3.3.2 Bomb radiocarbon

Beginning with the atmospheric nuclear weapons tests during the 1950s, the ¹⁴C content of the atmosphere and upper ocean increased sharply. As shown in Figure 8, oceanographers have been able to use the bomb ¹⁴C signal in the ocean as a primary data set with which to evaluate ocean circulation models on decadal time scales. Here the observed surface Δ¹⁴C values from the eastern Pacific GEOSECS stations and the WOCE P17 line are compared with the global ocean circulation model of Toggweiler and Samuels (1995a,b). Interpretation of the bomb signal in surface waters for one time period is difficult if the natural signal is not removed (Broecker *et al.*, 1985, Broecker *et al.*, 1995). But taking the difference between two time periods easily isolates the bomb signal. In doing so, we see that the model difference between 1973 and 1993 is much larger than the GEOSECS to WOCE difference, implying that the model is removing ¹⁴C from

Fig 8 Observed and modeled radiocarbon distribution in the surface waters of the Eastern Pacific in 1973 and 1993. 1973 observations are an average of GEOSECS observations east of the date-line and the 1993 observations are from the WOCE P17 line along 135°W. Observed values are taken from the shallowest sample above 100 m. The model used is from Toggweiler and Samuels (1995a, b), and values are taken from the surface grid box, which is 51 m deep, along 135°W.

the surface ocean (presumably downward) much faster than is actually occurring. This might suggest, for example, that this model would overestimate the uptake of anthropogenic CO_2 and the delivery of nutrients to the euphotic zone, particularly in the high latitudes.

We will simulate bomb radiocarbon in all four of our models following OCMIP guidelines, which are similar to the formulations of Toggweiler *et al* (1989b). The initial conditions will be the natural radiocarbon distribution simulated by each model, and the atmospheric history of radiocarbon from 1765 to the present will be specified. This extended time period is simulated so that the dilution of atmospheric and oceanic radiocarbon with fossil fuel CO_2 (the Suess effect) is taken into account.

3.3.3 Chlorofluorocarbons

To demonstrate the utility of CFCs in diagnosing ocean circulation, particularly those aspects relevant to the marine carbon cycle, we present an example from one of our own efforts (Caldeira) in Figure 9. Here CFCs reveal the great sensitivity of high latitude deep water formation to the parameterization of brine rejection during sea ice formation. Two simulations were performed: a Control simulation in which salt rejected during sea-ice formation is placed in the model's 25 m thick surface layer, and a Test simulation in which salt rejected during sea-ice formation is distributed uniformly throughout the upper 160 m beneath the forming sea ice. Distributing rejected salt more deeply during periods of ice formation helps to maintain vertical density gradients, inhibiting grid-scale convection and reducing vertical transport by isopycnal mixing. Both of these factors diminish the simulated absorption of CFC-11 and generally improve the model's CFC-11 and salinity fields. By 1990, the modeled global ocean inventory of CFC-11 is about 30% lower, and modeled column inventories in the Southern Ocean are up to 90% lower, in the Test simulation relative to the Control simulation. The simulations suggest that the vertical exchange processes that are so critical to the absorption of anthropogenic CO_2 and the upward transport of nutrients in high latitudes are highly sensitive to the parameterization of brine rejection.

As part of the proposed work, each of the four circulation models will simulate both CFC-11 and CFC-12. The gas transfer velocity for CFCs will be identical to that for CO_2 , except that there is no chemical enhancement and the Schmidt number, taken from Wanninkhof (1992), is different. The solubilities of CFC-11 and CFC-12 will be taken from Warner and Weiss (1985).

Fig 9 (a) Observed and (b and c) modeled distributions of CFC-11 between Tasmania and Antarctica in 1991. Observations are from the WOCE P-12 line (Bullister, personal communication, 1997). Salt rejected during sea ice formation is spread evenly throughout the top 25 m in the Control case (b) and top 160 m in the Test case (c).

The atmospheric record (from around 1930 to the present) will be the best agreed upon by R Weiss and co-workers.

4. Participating model descriptions

4.1. The circulation models

Ocean model results have been shown to be very sensitive to many factors, including turbulent mixing coefficients, model resolution, boundary conditions, and the representation of sub-grid-scale eddies, convective events, boundary layers, and plumes. Ideally, one would like to perform exhaustive parameter and parameterization studies to elucidate the robustness of model results to variations in these and other factors, so that some uncertainty estimates can be placed on model results. Unfortunately, this is generally costly and impractical because of the small timesteps and long integration times required for ocean models to reach equilibrium, particularly in the deep ocean. It is a goal of this study to provide some estimate of the reliability of model results by formalizing the comparison of results obtained by different groups working on the same set of problems, using different parameter values and different parameterizations.

Many marine carbon cycle models exist in the U.S. To achieve the goals of this project, we sought those that are (1) global in scale, (2) seasonally-resolved, (3) three-dimensional, (4) capable of long ($\sim 10^3$ yr) integrations (essentially requiring the models to parameterize mesoscale eddies). While there are other U.S. modeling efforts that satisfy these criteria (such as at the University of Miami), they are in collaboration with European OCMIP partners, and would therefore be redundant.

Of the models involved in this proposed evaluation and intercomparison project, three (Princeton, NCAR, and LLNL) are derived from the Geophysical Fluid Dynamics Laboratory (GFDL) ocean model, and one (MIT) has been independently developed (Table 2).

Table 2: Summary of ocean general circulation models (GCMs) to be used in this study.

feature	Princeton	NCAR	LLNL	MIT
GCM basis	MOM	MOM	MOM	MIT GCM
grid	B	B	B	C
horizontal resolution (lat $\times$ lon)	4.5° $\times$ 3.75°	3° $\times$ 3°	2° $\times$ 4°	4° $\times$ 4°
vertical levels	12	25	23	21
sub gridscale mixing	Griffies (1997)	Gent and McWilliams (1990)	Gent and McWilliams (1990)	Visbeck <i>et al</i> (1997)
finite differencing (advection)	centered/QUICKER	3rd-order upwind	centered	centered/ 3rd-order upwind
mixed layer	convective adjustment	Large <i>et al</i> (1994)	Large <i>et al</i> (1994)	convective adjustment
surface buoyancy forcing	T, S restoring	bulk formulae	T, S restoring/ bulk formulae	T, S restoring
ice model	no	yes	yes	no

4.1.1. The GFDL ocean general circulation models

GFDL has developed the most widely used global ocean model (Bryan and Cox, 1967), which in its more modern variations is known as the Modular Ocean Model (MOM; Pacanowski *et al.*, 1991). This basic model has undergone many enhancements and modifications, both at GFDL and at other institutions.

The basic model has a domain that is divided in the horizontal dimensions along a latitude-longitude grid, and divided in the vertical dimension into horizontal layers. The primary factors that need to be specified to the model are the horizontal and vertical grids, the bathymetry of the model ocean, surface boundary conditions, model time steps, and a variety of mixing and drag coefficients. Furthermore, at various institutions, researchers have experimented with different numerical advection schemes, mixed-layer representations, bottom-boundary layer representations, isopycnal mixing schemes, vertical mixing schemes, types of surface boundary conditions, coupling to sea-ice and/or atmosphere models, convective parameterizations, and so on. Variation in any of these factors, either singly or in combination, can significantly alter model results (e.g., Bryan, 1987, Bryan and Lewis, 1979) often in unexpected and as yet uncharacterized ways (see, for example, Figure 9).

Careful intercomparison of the results obtained by these three GFDL-derived models should help determine which model configuration best represents tracer transport in the ocean and why—and should help us to understand which physical processes most sensitively affect the simulated carbon cycle, thereby focusing future model development efforts.

Princeton The Princeton/GFDL global ocean model is the only U.S. model to have participated in the preliminary phase of OCMIP, and some of its characteristics have been described in radiocarbon studies by Toggweiler *et al.* (1989a,b) as well as solubility and biological pump simulations by Najjar (1992), Anderson and Sarmiento (1995), Sarmiento *et al.* (1996) and Sarmiento *et al.* (1997). The version of the model to be used in the proposed study has been significantly upgraded, and is based on the newest (as yet unreleased) MOM 2.2 code. Improvements include the incorporation of seasonality, isopycnal tracer mixing (Griffies *et al.*, 1997; Griffies, 1997, Gent and McWilliams, 1990), an improved higher-order (“QUICKER”) advection scheme, an open Bering Strait, a free surface formulation for freshwater fluxes, and a mixed layer model.

NCAR The NCAR CSM Ocean Model (NCOM), based on the MOM 1.1 code, has greatly advanced the state of the art of global ocean circulation modeling, largely through improved parameterizations of subgrid scale processes. The implementation of the Gent and McWilliams (1990) mesoscale eddy mixing parameterization diminishes the spurious upwelling and diapycnal diffusion of nutrients across western boundary currents (Sarmiento *et al.*, 1993) and the Antarctic Circumpolar Current typically found in z-coordinate models. A third-order up-winding advection scheme is included to reduce artificial numerical dispersion across steep tracer gradients as are found in the upper ocean (NCAR Oceanography Section, 1996). The planetary boundary layer scheme of Large *et al.* (1994) leads to more realistic exchange of properties between the surface layer and underlying seasonal thermocline (Doney *et al.*, 1996) and physical behavior under episodic atmospheric forcing (Doney, 1996). Finally, the replacement of the traditional surface restoring boundary conditions by bulk atmospheric surface forcing (NCAR Oceanography Section, 1996), produces improved annual cycles of SST and mixed layer depth as well as better solu-

tions for intermediate and deep water masses (Large *et al.*, 1997)

The physical initial conditions for the coupled biological-physical model are specified from a climate solution of the NCOM run to equilibrium (approximately 10,000 deep-water years) using numerical acceleration techniques (Large *et al.*, 1997). The equilibrium solutions were forced with monthly atmospheric climatologies (1985-1988). The sea ice fraction is diagnosed from a SST climatology, and local freezing (melting) of sea-ice is included but not horizontal advection of sea ice.

LLNL Though based on the MOM 1.1 code, the LLNL ocean general circulation model differs from MOM in several respects. The ocean model has been coupled to the dynamic/thermodynamic sea-ice model of Oberhuber (1993). The model includes one layer of snow and one layer of sea ice; it uses the viscous-plastic rheology of Hibler (1992). Surface fluxes of heat are calculated using the approach of Oberhuber (1993). Here, sensible, latent, longwave, and shortwave heat fluxes are calculated based on climatological atmospheric data and calculated sea surface temperatures. Furthermore, the model uses (1) the mixed-layer parameterization of Large *et al.* (1994), (2) a free surface approach to solving for barotropic velocities instead of making the standard rigid lid approximation, (3) the numerical scheme of Webb (1995) to minimize errors in vertical advection of momentum, (4) the Gent and McWilliams (1990) parameterization of transport of tracers by subgrid-scale eddies, and (5) an additional term to the vertical diffusion equation that partially cancels the numerical diffusion due to vertical advection (Yin and Fung, 1991). *We use a latitude-dependent horizontal viscosity that is higher near the equator to minimize Peclet-type instabilities in that region (Weaver and Sarachick, 1991; Robitaille and Weaver, 1995; Duffy et al., 1997). To further suppress Peclet-type instabilities near the equator, viscosity and/or diffusivity is locally and temporarily increased to prevent violations of grid-Reynolds and grid-Peclet conditions (Weaver and Sarachick, 1991). The latitudinal and vertical resolution is somewhat finer than the other models (Table 2) and was chosen to improve the representation of flow through the Drake passage, without artificial widening. The LLNL model runs on many different types of massively parallel computers.*

4.1.2 The MIT Ocean Circulation Model

The MIT general circulation model (GCM) solves the incompressible Navier-Stokes equations using finite volume techniques and was developed specifically for use on modern parallel computing platforms (Marshall *et al.*, 1997a,b). It need not make the hydrostatic approximation. The model has been applied to a large range of scales in the ocean, from studies of the details of the convective process in the ocean to global ocean circulation and estimation. In coarse resolution studies, geostrophic eddies are parameterized using the scheme outlined in Visbeck *et al.* (1997) which combines the best elements of the Transformed Eulerian Mean representation (Gent and McWilliams, 1990) with spatially and temporally variable mixing coefficients (Green, 1970, Stone 1972), which attempt to capture the strong regional variability of ocean eddy activity. A convective adjustment scheme (of the kind described by Klinger *et al.*, 1996) is used to parameterize convection.

4.2. The nutrient cycling models

The models described below are the “individual investigator” models of the organic matter

pump referred to earlier (Table 1). All of the models are nitrogen based, and will use fixed Redfield ratios to simulate carbon and oxygen cycling affected by the organic matter pump.

4.2.1 The LLNL productivity model

The basic approach to be used by the LLNL model is to estimate primary production in the upper ocean using satellite-based chlorophyll estimates (e.g., Behrenfeld and Falkowski, 1997, Longhurst *et al.*, 1995), and then estimate export production using a nitrate-based *f*-ratio approach (e.g., Harrison *et al.*, 1987), where the *f*-ratio is taken to mean the ratio of new production to total production. This model is similar to the nutrient restoring approach in that it is constrained by observations, though an additional degree of freedom is allowed by making nitrate the only prognostic variable of the model. This approach is somewhat problematic because the *f*-ratio may deviate from the nitrate-based relationship under certain circumstances, such as during blooms and if other nutrients are limiting. Some of these concerns will be addressed by developing an improved empirical *f*-ratio estimate based both on nutrient concentrations and oceanographic conditions predicted by the model (e.g., whether upwelling zone or not). The *f*-ratio approach does have one very attractive property when compared with sinking-rate or other non-nutrient based methods of estimating export from primary production: by coupling export production to nutrient concentrations directly, the model is assured of computing nutrient concentrations that are greater than or equal to zero everywhere. Organic matter exported from the euphotic zone will be remineralized instantly following length scales given by sediment trap observations (e.g., Martin *et al.*, 1987). The export production model will take a primary production model directly from the literature; the *f*-ratio export production parameterization and incorporation of the model into the ocean GCM will be developed under separate funding.

4.2.2 The MIT nutrient model

The MIT group will adopt a more prognostic approach by parameterizing new production as a function of surface irradiation and euphotic zone nutrient concentration (Bacastow and Maier-Reimer, 1990). As with the LLNL model, nitrate is the only prognostic variable transported by the model. The parameters for light and nutrient dependence of new production are taken from Yamanaka and Tajika (1996) and remineralization below the euphotic zone is treated as in the LLNL model. Though simple, this parameterization of nutrient cycling can capture the first-order large-scale patterns of the ocean's nitrate distribution (Bacastow and Maier-Reimer, 1990, Yamanaka and Tajika, 1996).

4.2.3. The Princeton ecosystem model

The next level of sophistication is represented by process-based models developed at Princeton for use in seasonal simulations (Hurtt and Armstrong, 1996). To better capture food web dynamics, this approach adds two state variables beyond nutrients: *P* (phytoplankton) and *R/E* (remineralization/export). This structure avoids certain problems inherent in traditional "NPZ" food web models (notably the tendency of *P* to be held near a single yearly average value independent of location [Armstrong *et al.*, 1995]) while allowing the parameterization of other important attributes of real systems (notably the prevalence of small phytoplankton size classes in oligotrophic situations and the addition of larger phytoplankton size classes under more eutrophic

conditions) The current version contains both variable chlorophyll nitrogen ratio (Sakshaug *et al*, 1989) and iron limitation

From a global carbon perspective, an important goal is to construct a general model that can be used everywhere in the world ocean with only minor adjustments to the values of a few parameters. The Princeton model has been calibrated in a mixed-layer physical model (similar to that used by Fasham *et al* [1990]) and can simultaneously fit time-series data on nitrate, chlorophyll, and productivity from oligotrophic (BATS) and seasonally eutrophic (OWS India) by varying only two parameters representing the degree of iron limitation and water clarity The model is currently being adapted and modified for use in a global context

4.2.4 The NCAR marine ecosystem model

A third approach, represented in OCMIP by the NCAR ecosystem model (Doney *et al.*, 1996), is to explicitly model the trophic interactions between producers and grazers, commonly expressed by the so-called NPZD (nutrient, phytoplankton, zooplankton, detritus models, e.g. Fasham *et al*, 1990). Phytoplankton growth in the NCAR model is controlled by nutrient and light limitations, including the effects of vertical variations in bio-optical spectral quantities (Anderson, 1993), variable chlorophyll:nitrogen ratios based on queuing theory (Kiefer, 1993, Geider *et al.*, 1996), and implementation of a crude iron limitation parameterization Phytoplankton losses occur via natural mortality, zooplankton grazing and phytoplankton aggregation, the latter two processes leading to the production of sinking detrital particles The effect of secondary production by bacteria, the so-called “microbial” loop (e.g., Ducklow, 1983), is treated indirectly by the parameterizations of nutrient regeneration and particle remineralization

A 1-D version of the Doney *et al* (1996) model shows significant skill in capturing the major features of the annual chlorophyll field (e.g., spring bloom, deep chlorophyll maximum) and depth integrated chlorophyll and primary production as exhibited by the BATS data Successful simulations of the annual cycle for ocean weather station PAPA, an HNLC site in the subpolar North Pacific, also have been completed (Evans and Garçon, 1997) As discussed early (Section 1, Figure 2) a global version has also been created for comparison with satellite ocean color data (Glover and Doney, 1997) and shows significant skill in simulating both the spring bloom in the high latitude North Atlantic and locations of the subpolar/subtropical chlorophyll transition zone

5. Analysis of model results

The three main phases of the project consist of simulations, standard analysis and extended analysis (Figure 10) Standard analysis refers to the basic processing of the model output, which will include, for example, zonal and horizontal averages of the various tracers (phosphate, oxygen, DIC, Alk, anthropogenic CO₂, CFCs, and radiocarbon), as well as analyses of important fluxes (new production, air-sea CO₂ and oxygen fluxes, etc.). Standard analysis also includes similar processing of corresponding observational data sets Extended analysis refers to a more in-depth analysis that seeks to answer specific questions, such as the relative importance of the solubility and biological pumps, estimating the uncertainties of the model-based estimates of anthropogenic CO₂ uptake, determining the causes for model-model and model-observation differences, and estimating the lifetime of nutrients in surface waters

6. Project management structure

Figure 10 Project milestones See text for explanation of standard and extended analyses

This project will be coordinated and managed at The Pennsylvania State University by Raymond Najjar. To insure that the U.S. and European modeling groups follow the same protocols for simulations and analyses, Najjar will work closely with James Orr (IPSL), who is coordinating the European effort. The U.S. modeling groups (Caldeira, Doney, Follows/Marshall, and Sarmiento) will be responsible for conducting the simulations on their own computers and submitting the results to Penn State via the Internet in standard format. The Europeans plan to do the same, submitting their results to IPSL. Sabine, Key and Najjar will be responsible for assembling data sets for DIC and alkalinity, radiocarbon, and nutrients and oxygen, respectively. Sabine will work and meet regularly with other experimentalists (e.g., Rik Wanninkhof, Richard Feely, Taro Takahashi, Doug Wallace) to create a global synthesis of DIC and alkalinity measurements, as well as derived products, such as anthropogenic DIC. The standard analysis of model results will be performed at Penn State by a post-doctoral associate supervised by Najjar. All OCMIP groups (U.S. and European) will have access to all model results on both Internet sites so that each group can pursue their own extended analysis of the model results. A standardized software package will be created at IPSL and Penn State in order to facilitate analysis of model results. This software package will be made available to all participants.

Model results and data syntheses will also be made available to the general scientific community approximately one year after the completion of model runs and syntheses. These data sets will be placed on a publicly accessible Internet site at Penn State and/or IPSL.

7. Budget discussion

We are mainly requesting salary and personnel support for this project. In most cases, all of the simulations and analyses will be carried out on existing computational facilities at our own laboratories. In general, with the exception of Sarmiento, who already has support to carry out the proposed simulations and analysis, we are requesting several months per year for each modeling

and data synthesis group. Some of us are requesting support for ourselves, while others are requesting support for additional personnel, such as a programmer or post-doctoral associate.

Because this is a collaborative proposal that will coordinate with other investigators on an international level, it is crucial that the lines of communication are maintained among all of the groups involved. We have each requested enough travel funds so that the U.S. groups can meet amongst themselves once per year, possibly at national meetings. Additionally, we will meet once per year with the European OCMIP groups, though support for this will be provided by the GAIM office (see letter in Section I).

8. Summary

We recognize that there are a number of limitations to the proposed research. For example, all of our simulations are climatological, and therefore allow only indirect comparisons to the JGOFS process studies, which are necessarily synoptic in nature and contain significant interannual variability. On the other hand, the JGOFS time-series data near Bermuda (BATS), Hawaii (HOT), the Canary Islands (EUMELI) and Kerguelen Island (KERFIX), from which climatological annual cycles can be derived, will be of great use for model evaluation. Also, deep ocean data sets, such as those from the JGOFS CO₂ survey, likely have a very small time-varying component and therefore should be of great use in evaluating our models. Another shortcoming is that even though eddies abound in the ocean and clearly impact marine biogeochemical processes—as the JGOFS data sets testify to—none of the models to be used in this study are eddy-resolving. The choice of using coarse resolution models was based on the need to capture the climatological annual cycle and long-term steady state behavior of the marine carbon cycle, time scales that are probably the most relevant for determining the air-sea partitioning of CO₂. We believe that studies that address these weaknesses are very important, and some of us are pursuing research studying the impact of short-term, interannual and mesoscale variability on marine biogeochemical systems. Our view is that regional and local studies focussing on short-term and interannual variability will help to identify important areas of model development. An excellent example is the recent JGOFS intercomparison/evaluation workshop of one-dimensional ecosystem models (Evans and Garçon, 1997). Results from such studies will ultimately lead to improved parameterizations for global scale models.

Despite these limitations, we believe that the confluence of marine biogeochemical expertise (from modelers and observationalists) and relevant observational data sets (from JGOFS, satellite and historical sources) represents a unique opportunity for rapidly accelerating the development of global marine carbon cycle models. Because we will be closely collaborating with a similar European effort, we will extend the strong and successful international flavor evident in the JGOFS field programs to the current synthesis and modeling phase. This proposal also will serve to bring two IGBP programs, JGOFS and GAIM, more closely together because of the common goals of these programs: to develop biogeochemical models for use in Earth-system climate models (see letter from Roger Hanson in Section I). By pooling resources—intellectual and computational—progress can be made more rapidly and more efficiently than if modelers, observationalists and data synthesists were to work in isolation. We therefore expect the payoffs of this project in terms of our understanding the marine carbon cycle and how it affects the air-sea partitioning of CO₂ to be substantial.

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